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AFWAL-TR-88-3082



# AFTI/F-111 MISSION ADAPTIVE WING BRIEFING TO INDUSTRY



Boeing Advanced Systems Co.
Seattle WA

October 1988

Final Report for Period Nov 86 to Jul 88

Approved for public release; distribution unlimited

FLIGHT DYNAMICS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6553

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

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This report is a collection of charts presented at the 21-22 July 1988 AFTI/F-111 Briefing to Industry. A copy is to be mailed to each Briefing attendee.

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|---|---|---|
| 01 | 01 | |
| 01 | 04 | |

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Smooth variable camber wing, Flight test results.
Automatic flight controls.

19. ABSTRACT (Continue on reverse if necessary and identify by block number)


The AFTI/F-111 (Advanced Fighter Technology Integration/F-111) Mission Adaptive Wing is a joint USAF and NASA program which is developing and flight demonstrating a smooth variable camber wing and flight control system capable of adjusting the wing's shape in response to flight condition and pilot input in order to maximize aerodynamic efficiency. The program objective is to produce flight substantiated design criteria for a practical wing system that maintains peak aerodynamic efficiency and versatility throughout the broad flight envelopes and diverse mission requirements of future military and civilian aircraft.

This document contains illustrations presented at the second AFTI/F-111 Mission Adaptive Wing Briefing to Industry on 21-22 July 1988 in Dayton OH. The presentations covered the analysis, design, ground test, and flight test phases of the development of the automatic flight control system for the AFTI/F-111. An earlier Briefing to Industry in November 1986 covered all phases of the AFTI/F-111 manual system development.


(continued on reverse side)

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| 22a. NAME OF RESPONSIBLE INDIVIDUAL<br>Kenneth L. Bonnema | 22b. TELEPHONE (Include Area Code)<br>(513) 255-6739<br>22c. OFFICE SYMBOL<br>AFWAL/FIMF |

Block 19. ABSTRACT (Cont.)

Flight testing of the AFTI/F-111 Mission Adaptive Wing system was only partially complete at the time these illustrations were prepared for presentation. Data and findings herein should be considered preliminary. [illegible]; Variable leading edges; Variable trailing edges,

## FOREWORD

The AFTI/F-111 (Advanced Fighter Technology Integration/F-111) Program began as a joint USAF/NASA effort in 1975 with several exploratory studies to evaluate ability of state of the art technologies to be integrated into a wing system capable of maintaining peak aerodynamic efficiency for future fighters and bombers. As the concept matured, it was dubbed the Mission Adaptive Wing (MAW). A contract was awarded to the Boeing Company in 1979 to design and fabricate a flight research version of the MAW for flight testing on NF-111A aircraft number 13. The objective: to produce flight test substantiated design criteria for practical wing systems that maintain peak aerodynamic efficiency and versatility throughout diverse missions by changing wing contour in response to variable flight condition, aircraft configuration, and pilot commands. The overall program management, as well as Boeing's design and fabrication, were provided by USAF's Flight Dynamics Laboratory. The flight testing was performed by NASA's Ames Dryden Flight Research Facility with the assistance of the Air Force Flight Test Center (AFFTC). Other contributors to the development: NASA/ARC, U.S. Navy/ONR, NASA/LARC, USAF/AEDC, Grumman Corporation, and General Dynamics Corporation.

This document contains illustrations presented at the Second AFTI/F-111 Briefing to Industry on 21-22 July 1988 in Dayton, Ohio. The program was in the midst of its second flight test phase at the time of the Briefing to Industry. The second phase of flight testing focuses primarily on the evaluation of the AFTI/F-111 automatic flight control system. This emphasis was reflected at the Briefing to Industry, with the majority of the presentations addressing automatic flight control system topics.

Data and findings contained herein should be considered preliminary. Five months of flight testing remain, and final conclusions may be revised based on the outcome of the remaining tests. A Mission Adaptive Wing Symposium is planned for the spring of 1989, at which final results, conclusions, and design criteria will be presented.

AFTI/F-111 MISSION ADAPTIVE WING
SECOND BRIEFING TO INDUSTRY, 21-22 JULY 1988
STOUFFER'S CENTER PLAZA HOTEL, DAYTON OH

THURSDAY, 21 JULY 1988

0745-0830 Registration
0830-0900 Welcome & Introduction - Col Thaddeus Sandford, FDL Director

SESSION I - AFTI/F-111 Program Summary and Review
0900-0915 Mission Adaptive Wing Background - Ron DeCamp (FDL)
0915-0945 MAW System Development Review - Doug Gould (Boeing)
0945-1000 MAW Flight Test Overview - Louis Steers (NASA)
1000-1015 Break

SESSION II - Manual Flight Control System Flight Test Results
1015-1045 Performance & Stability & Control - Steve Smith (AFFTC)
1045-1105 Wing Loads Summary - Steve Thornton (NASA)
1105-1130 Wing Pressure Distributions - Dean Webb (NASA)
1130-1200 Buffet Characteristics - Ed Friend (NASA)
1200-1300 Lunch

SESSION III - Automatic Flight Control System Development
1300-1330 AFCS Objectives and Requirements - Aivars Smitchens (FDL)
1330-1355 Cruise Camber Control Mode Development - Joe Hall (Boeing)
1355-1415 Maneuver Camber Control Mode Development - George Lewis (Boeing)
1415-1445 Maneuver Load Control Development - George Lewis (Boeing)
1445-1500 Break
1500-1530 Maneuver Enhancement/Gust Alleviation Mode Development - Dan Norman (Boeing)
1530-1545 AFCS Mode Combination Capabilities - Joe Hall (Boeing)
1545-1615 AFCS Simulation - Joe Hall (Boeing)
1615-1645 Fabrication & Ground Testing of AFCS - Clete Boldrin (Boeing)
1645-1705 Government Overview of Software Development - Ron Braet (FTI)

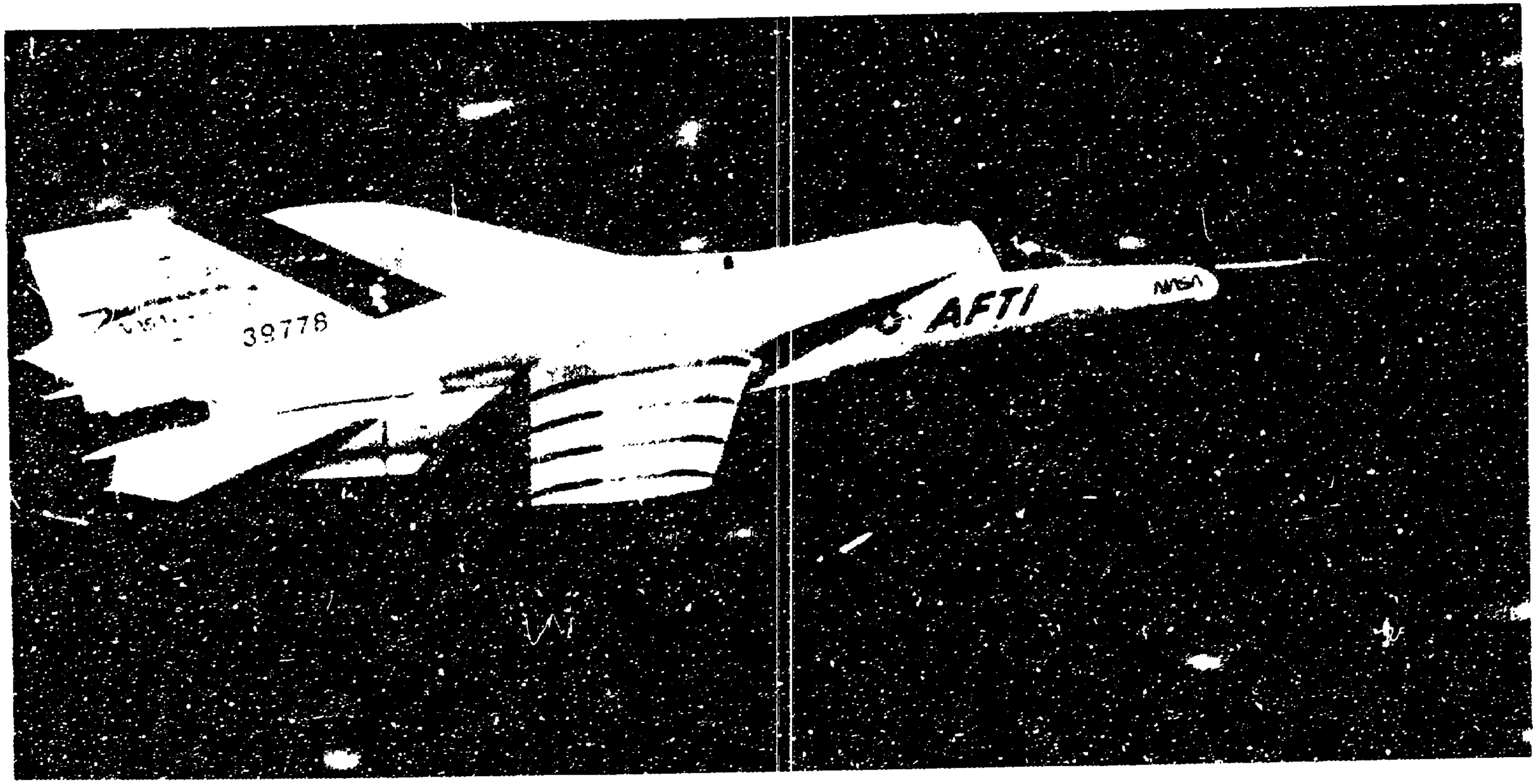
FRIDAY, 22 JULY 1988

SESSION IV - Automatic Flight Control System Flight Test Results
0800-0845 AFCS Functional & Performance Results - P. Bussing (Boeing), P. Phillips (AFFTC)
0845-0900 Handling Qualities of MCC - Joe Conley (NASA)
0900-0915 AFCS Handling Qualities - Gordon Fullerton (AFFTC)
0915-0930 AFTI/F-111 Mission Performance - Glenn Harshberger (FDL)

SESSION V - MAW Technology Transition
0930-0950 Cruise Camber Control Mode Evaluation - Col Larry Brock (USAFR)
0950-1010 Automodes Analysis - Joe Conley (NASA)
1010-1025 Break
1025-1045 Structures and Mechanization Lessons Learned - Frank Statkus (Boeing)
1045-1100 Flight Control System Lessons Learned - Joe Hall (Boeing)
1100-1120 Considerations for an Operational MAW System - Doug Gould (Boeing)

SESSION VI - Future Research
1120-1130 Overview of the Remaining Flight Test Program - Louis Steers (NASA)
1130-1150 Summary Comments - Dr Keith Richey, AFWAL Technical Director
1150-1200 Closing Remarks - Ron DeCamp (FDL)

# AFTI/F-111 MISSION ADAPTIVE WING BRIEFING TO INDUSTRY




21-22 JULY 1988 DAYTON, OHIO

## SESSION I

## AFTI/F-111 PROGRAM SUMMARY AND REVIEW

# MAW SYSTEM DEVELOPMENT REVIEW

Douglas K. Gould
Boeing Advanced Systems

# Mission Adaptive Wing Definition

The Mission Adaptive Wing combines:

Variable Wing Geometry

A flight control system for automatic wing geometry change according to various pre-determined operating modes

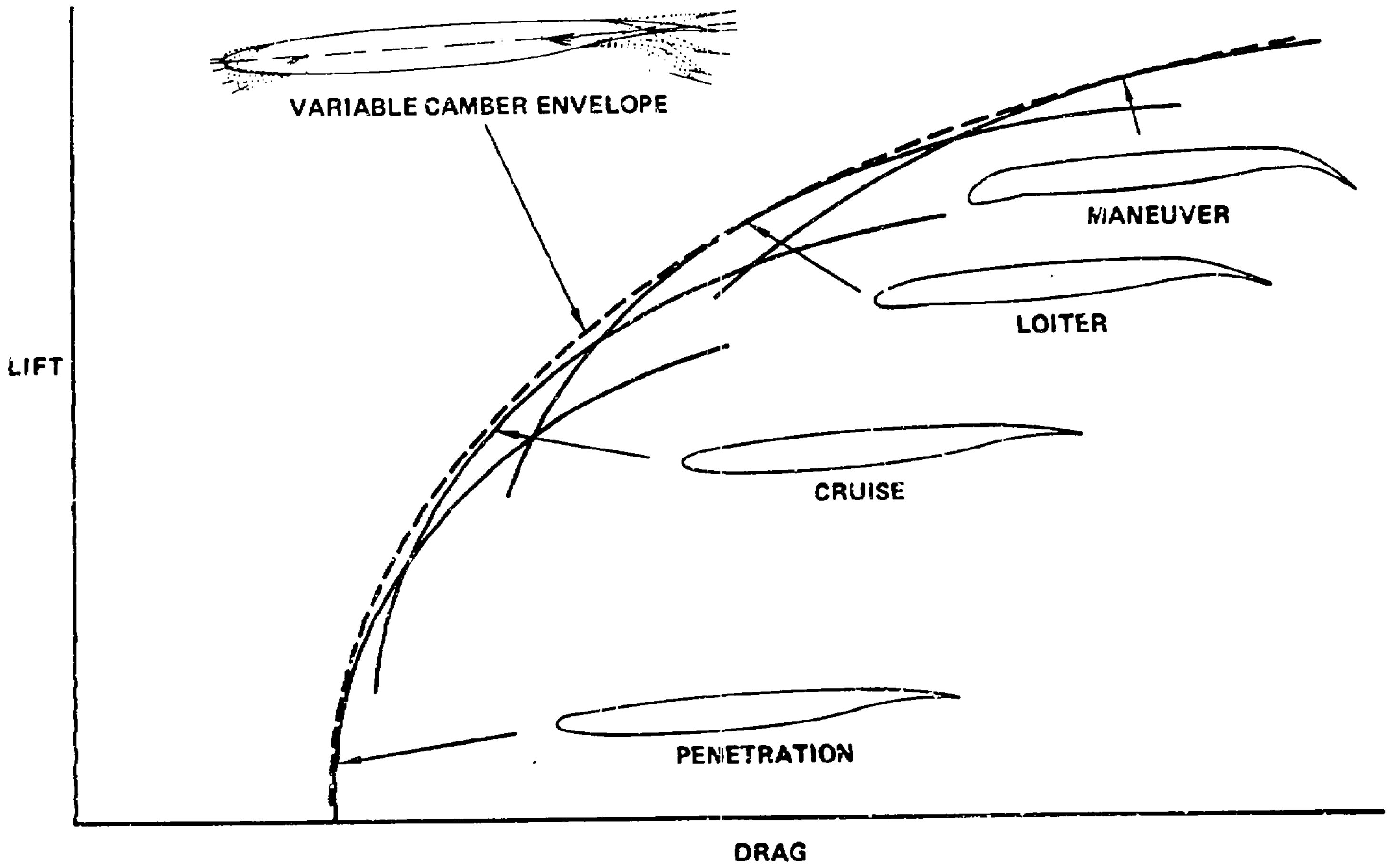
# Objectives

- Improved aerodynamic efficiency over a wide range of flight conditions

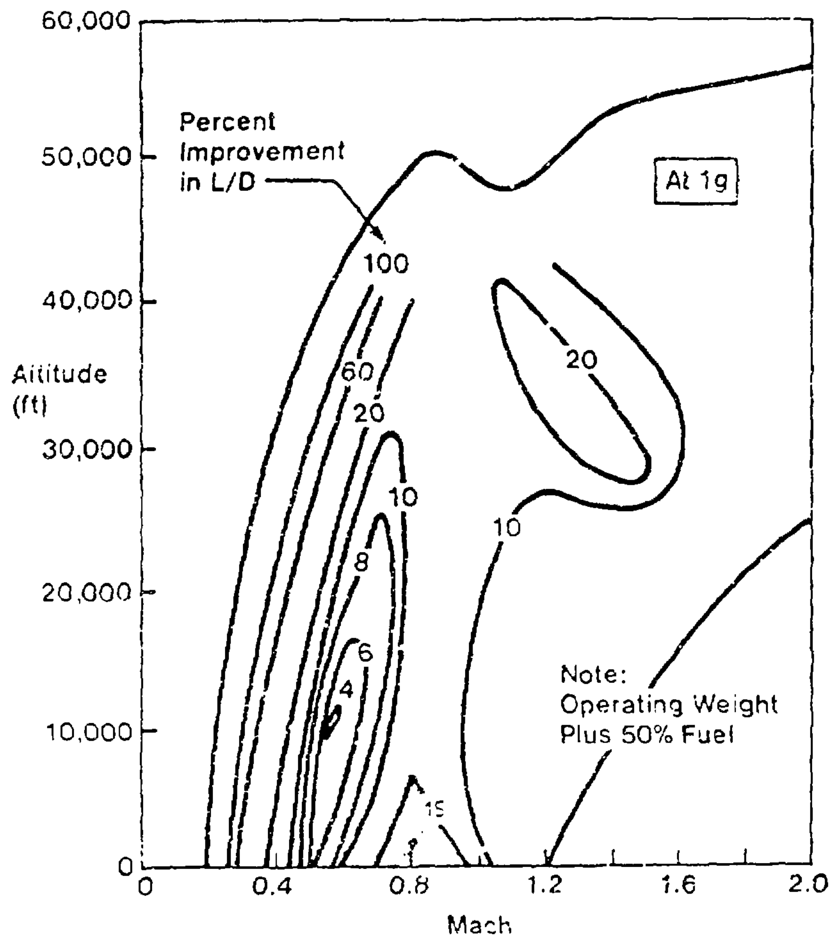
- Improved maneuver and dynamics capability
    - Response time
    - Load alleviation

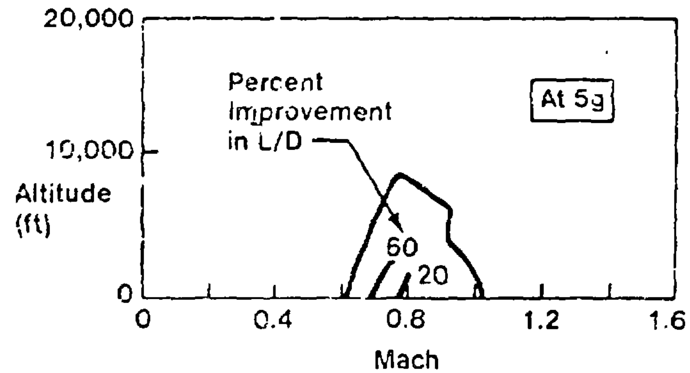
- Provide basic data for application to future aircraft systems

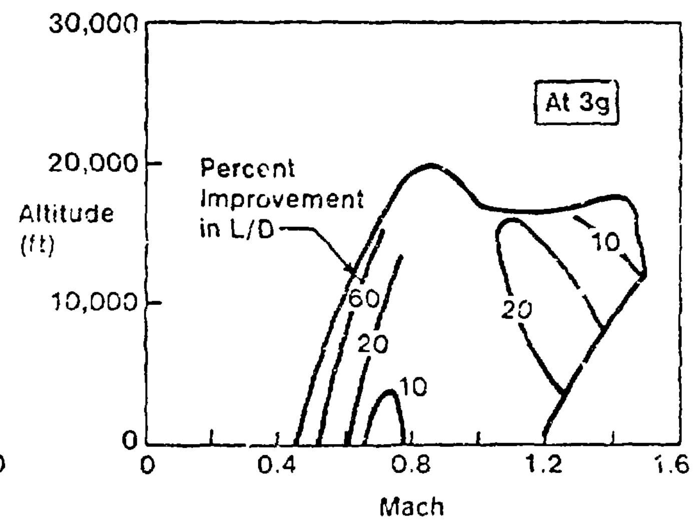
# Mission Adaptive Wing
# Aerodynamic Characteristics



# Increased Aerodynamic Efficiency



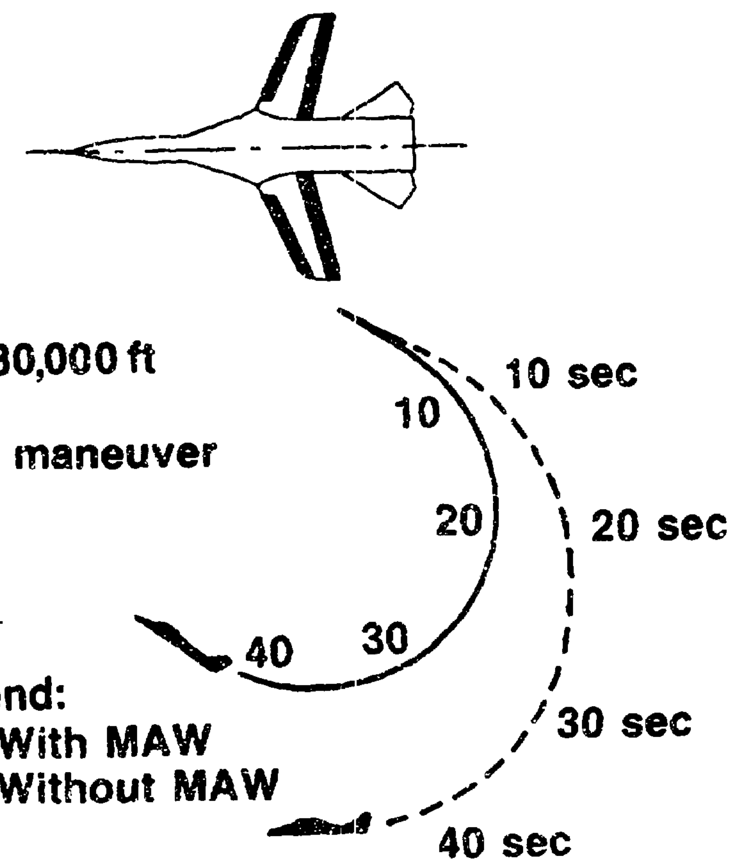
# Mission Adaptive Wing Operating Modes

- Four modes
  - Maneuver camber control (MCC)
  - Cruise camber control (CCC)
  - Maneuver load control (MLC)
  - Maneuver enhancement and gust alleviation (ME/GA)

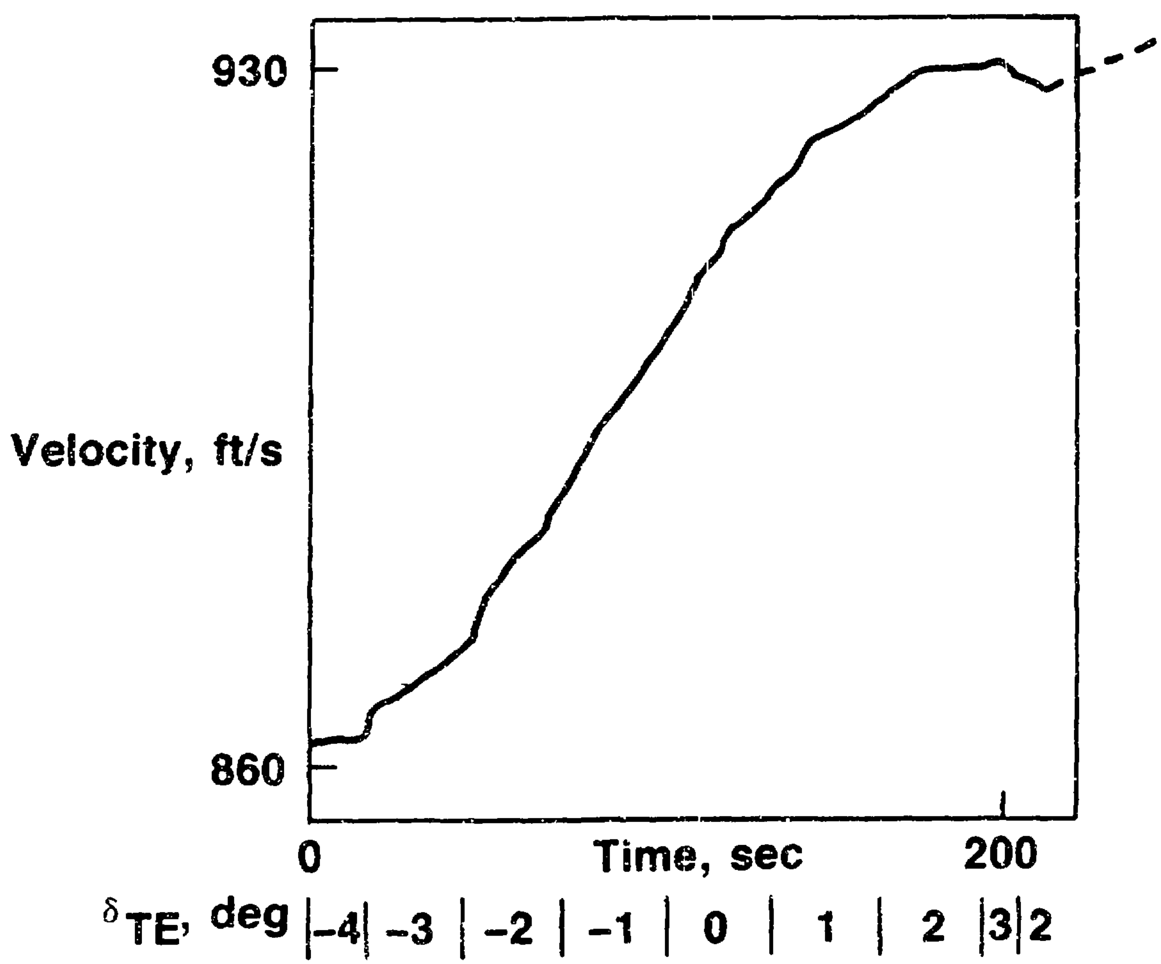
- Modes integrated as system
  - MCC and CCC
  - MCC, MLC, ME/GA
  - Verifiable and demonstrable as individual modes or as integrated system

# Maneuver Camber Control—Sustained Maneuver Comparison

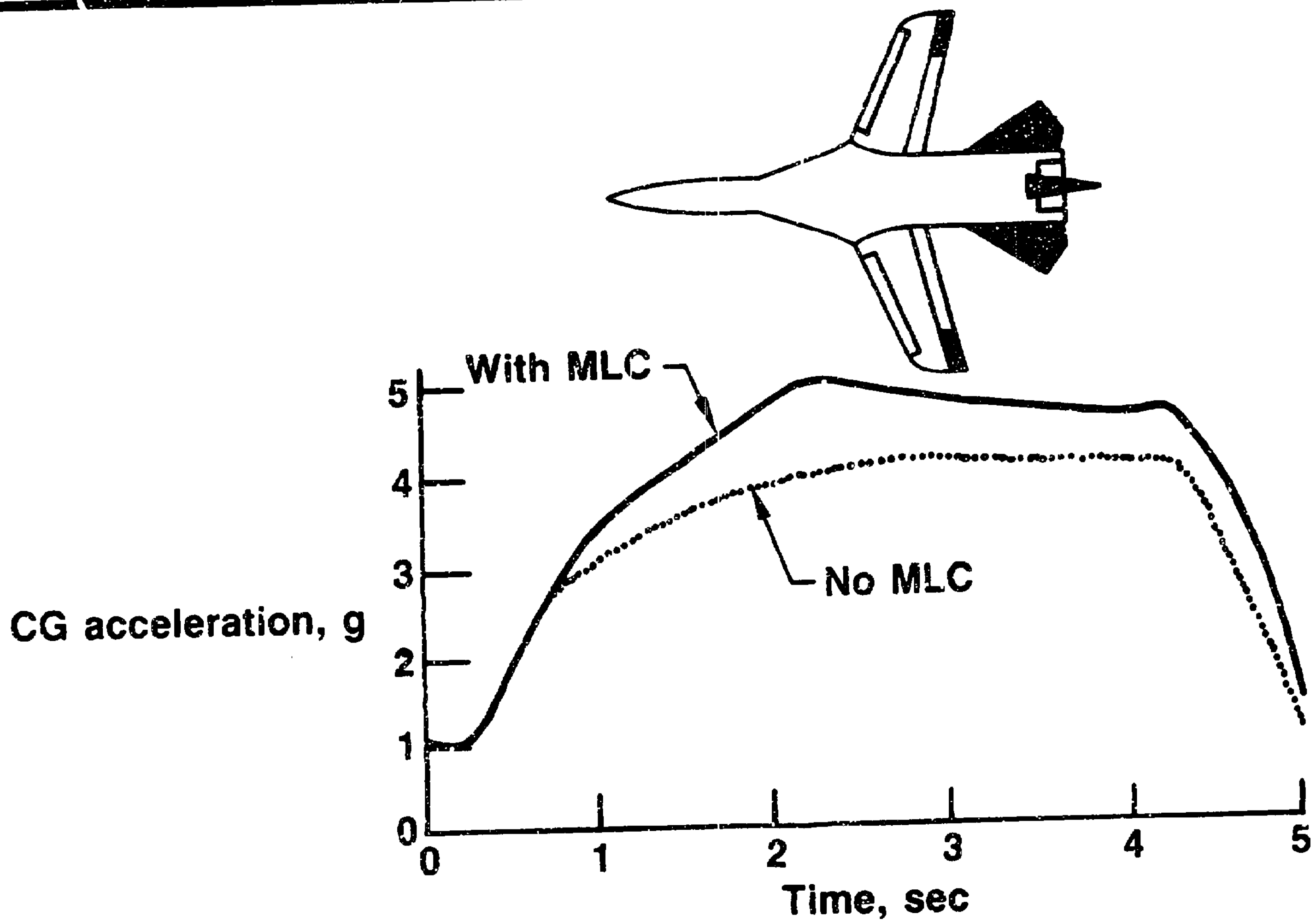
Conditions:
- Altitude: 30,000 ft
- Mach: 0.6
- Sustained maneuver



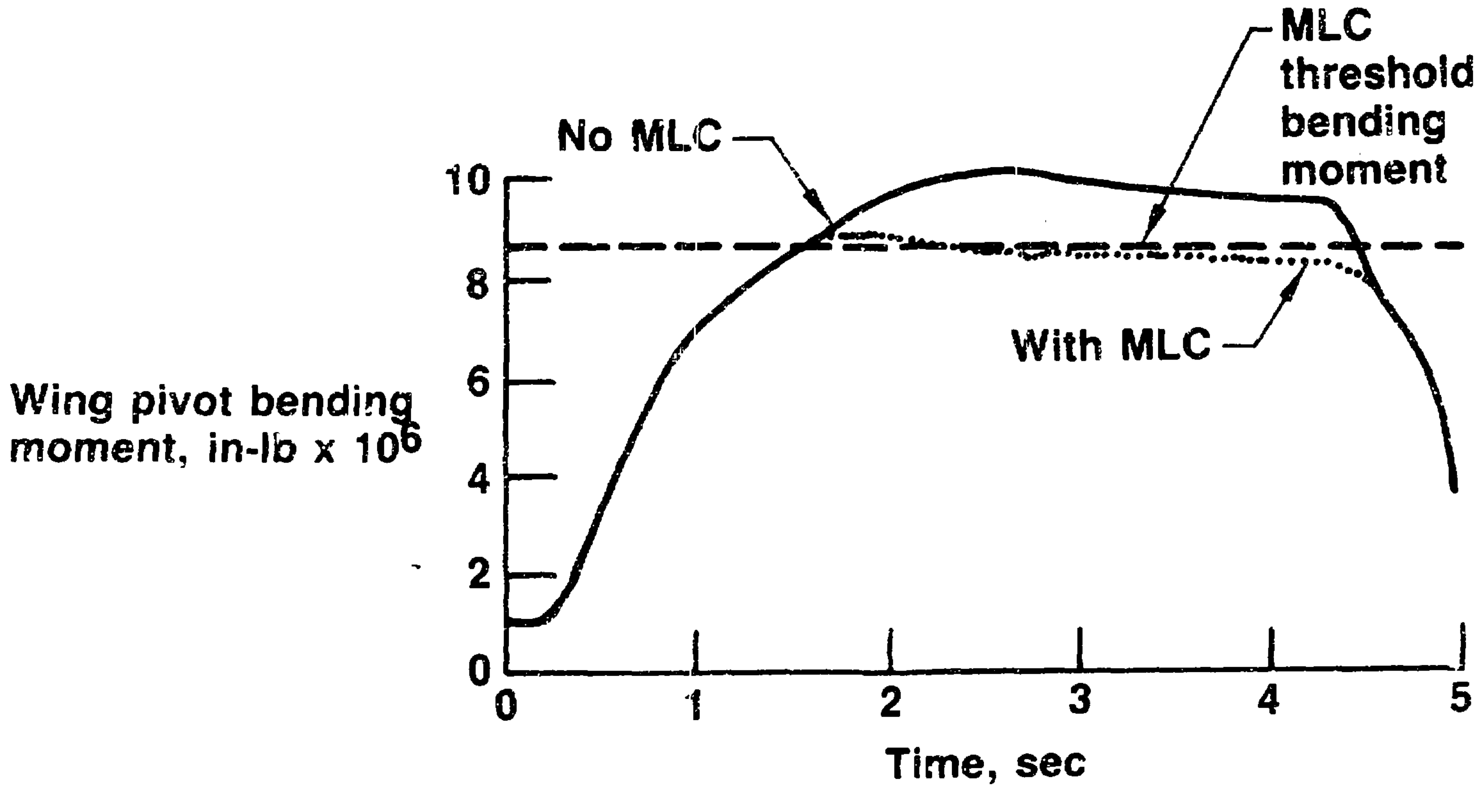
# Cruise Camber Control



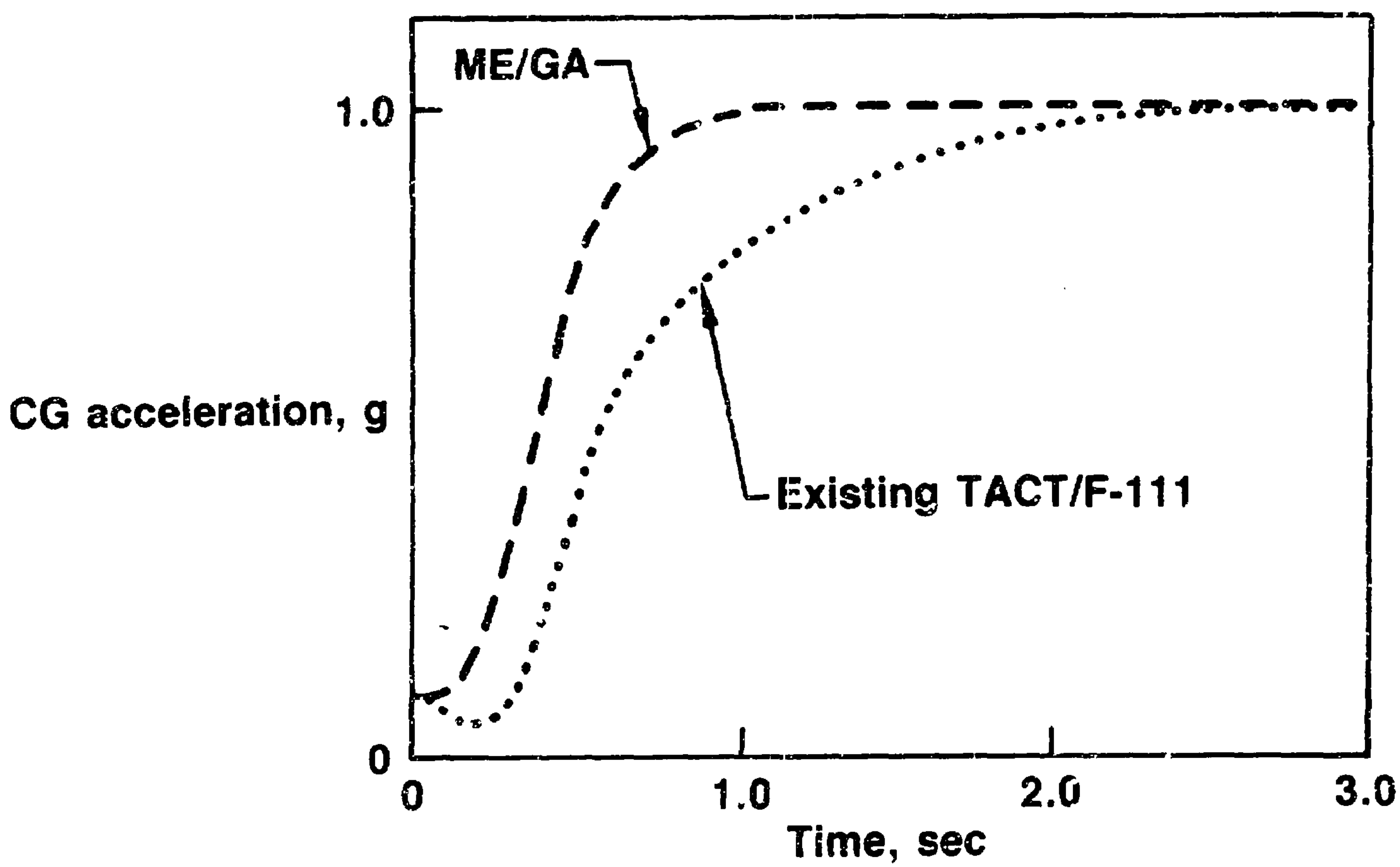
# Maneuver Load Control at Constant Bending Moment (8.5 in-lb x $10^6$)



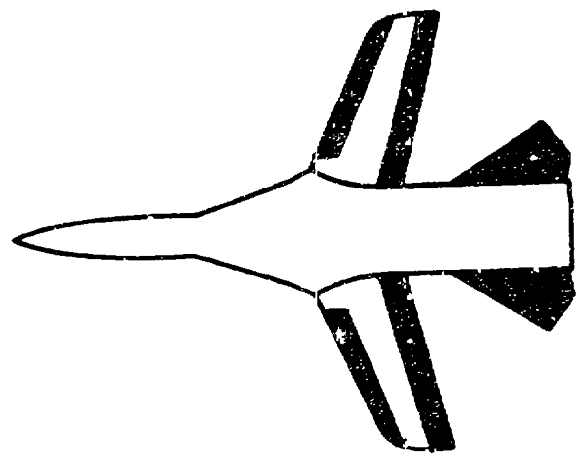
# Maneuver Load Control at Constant 5g



# Maneuver Enhancement and Gust Alleviation—Typical $N_Z$ Response



# Maneuver Enhancement and Gust Alleviation—Gust Response Summary

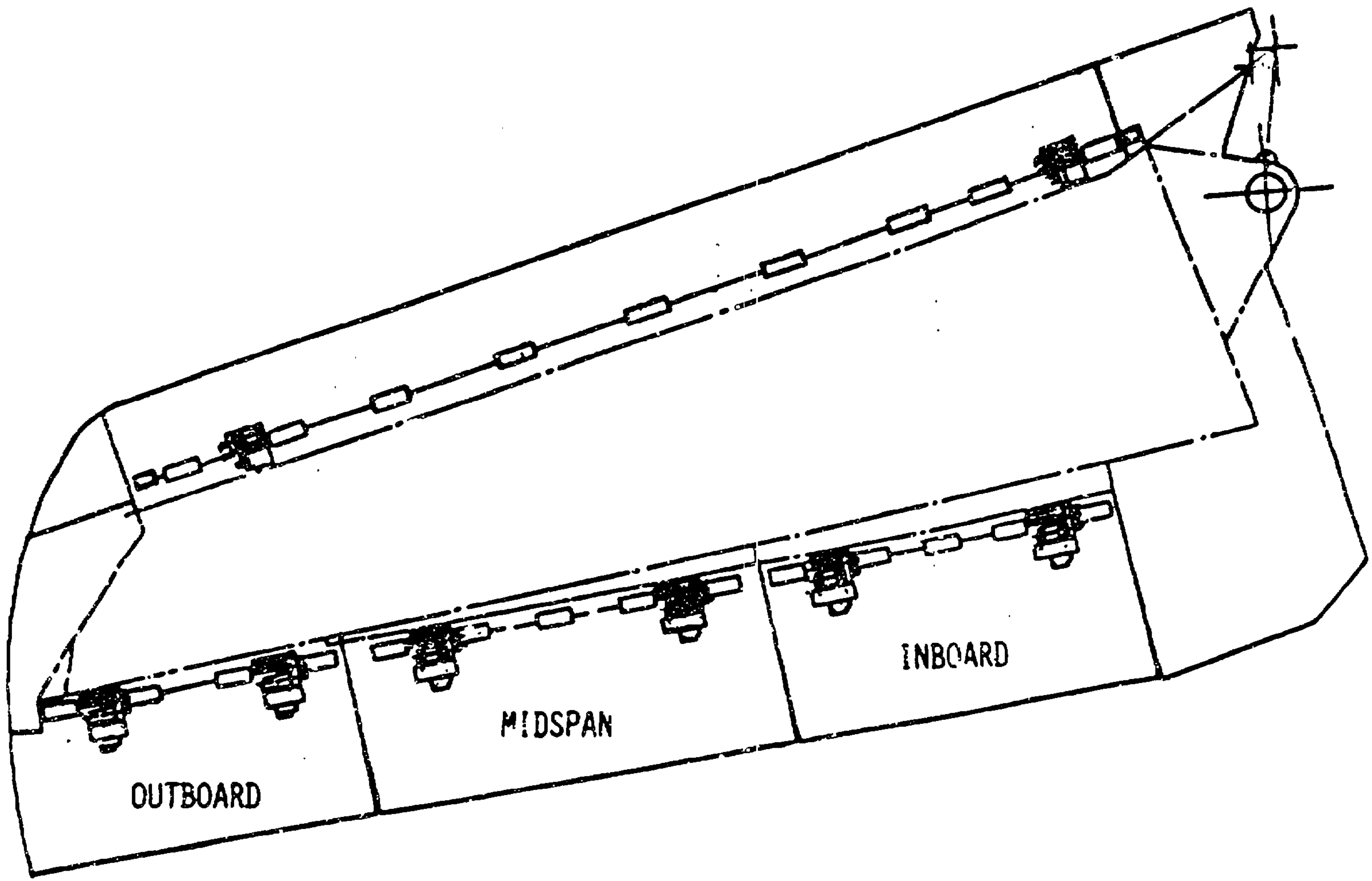


- Reduction of aircraft open-loop response with ME/GA
  - NZ at cockpit: 39%
  - NZ at CG: 23%

Conditions:

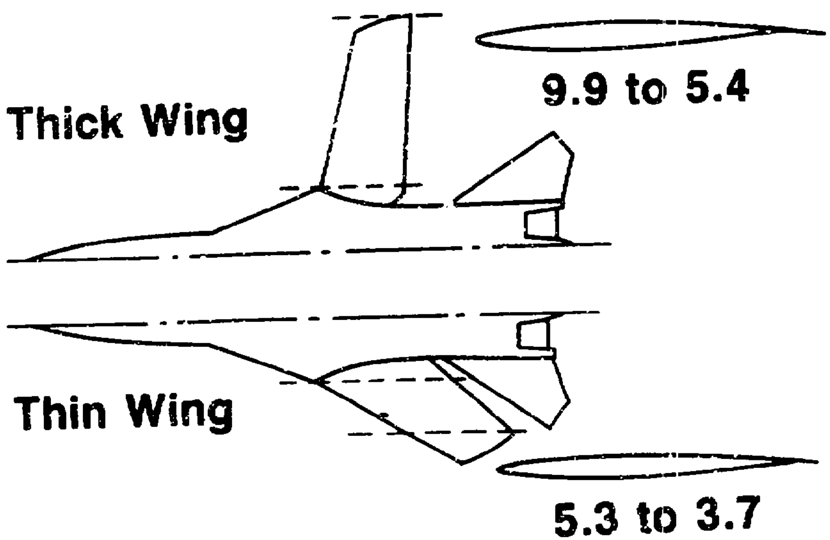
- Height: 15,000 ft
- Mach: 0.8
- Weight: 73,000 lb

# AFTI-F-111 GENERAL ARRANGEMENT MECHANICAL SYSTEM



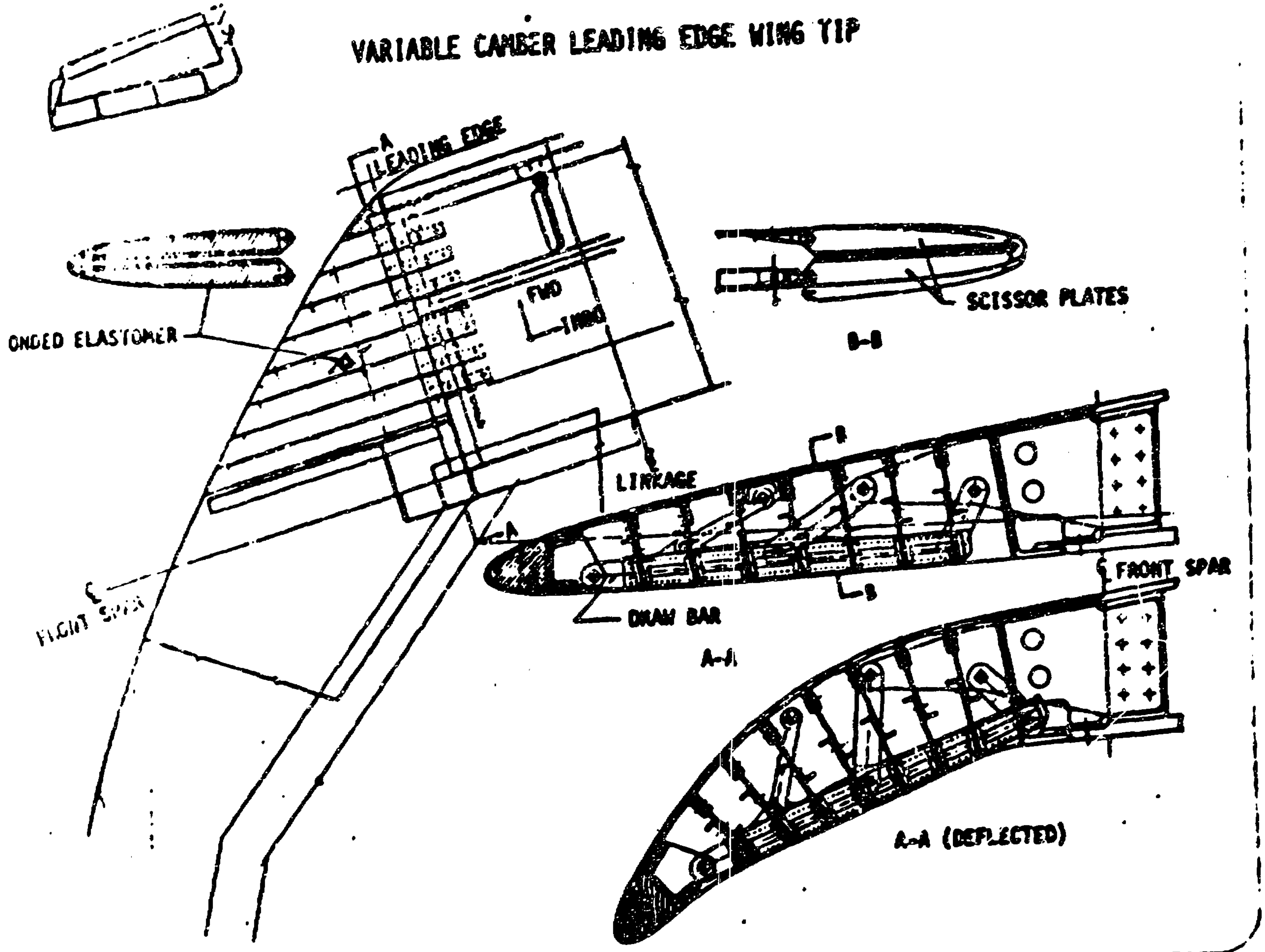
# AFTI/F-111 MAW Applicability to Thin and Thick Wings

AFTI/F-111 research configuration $t/c_{max}$ range, %




| Existing aircraft | $t/c_{max}$ range, % |
|---|---|
| A-7 | 7 |
| C-5 | 12 to 11 |
| A-10 | 16 to 13 |
| C-130 | 18 to 12 |
| Concorde | 3 to 2.2 |
| F-15 | 6.6 to 3 |
| F-16 | 4 |

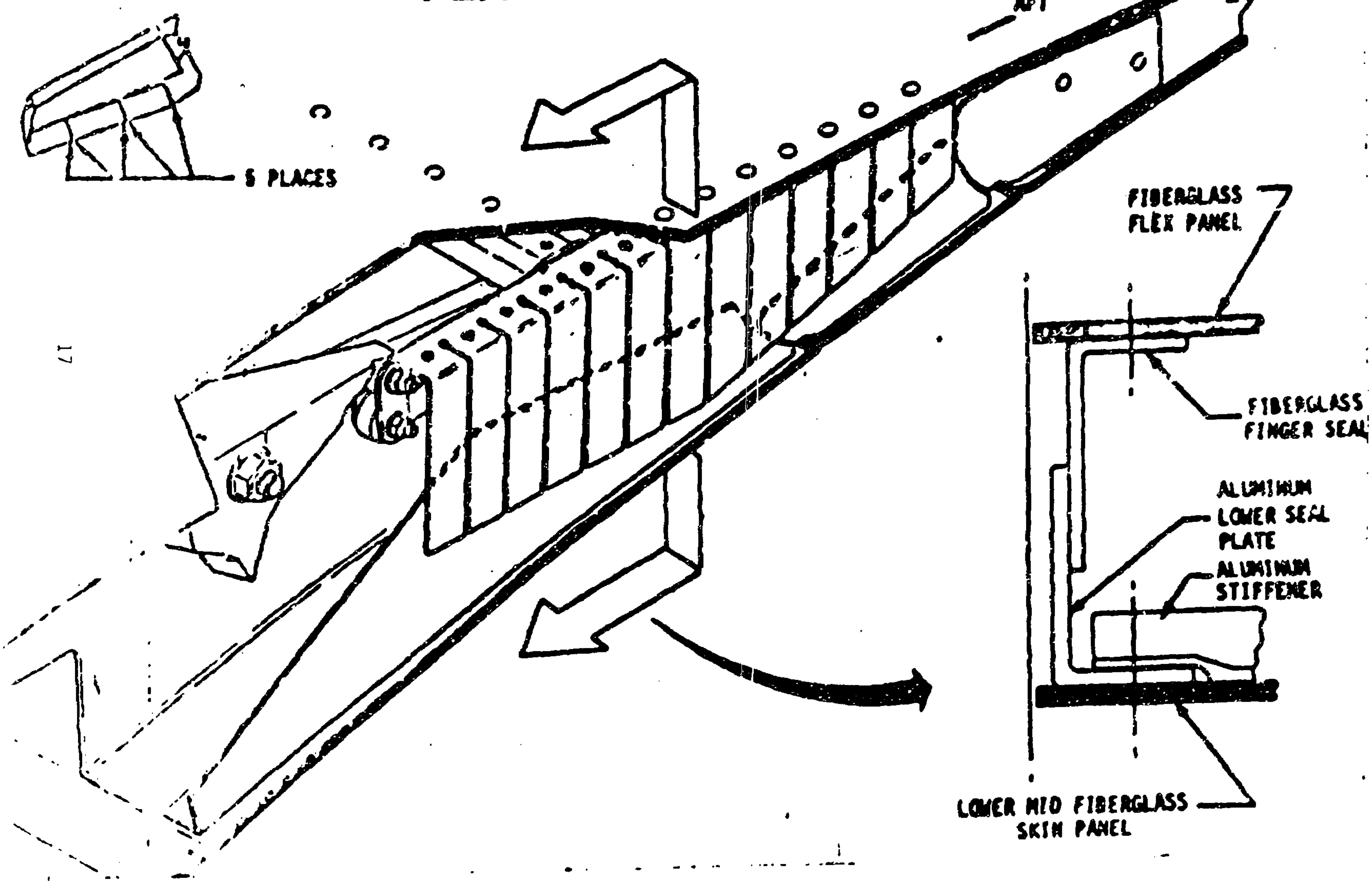
VARIABLE CAMBER LEADING EDGE WING TIP




Contd Blocks Sliding In A Channel

# TRAILING EDGE VARIABLE CAMBER

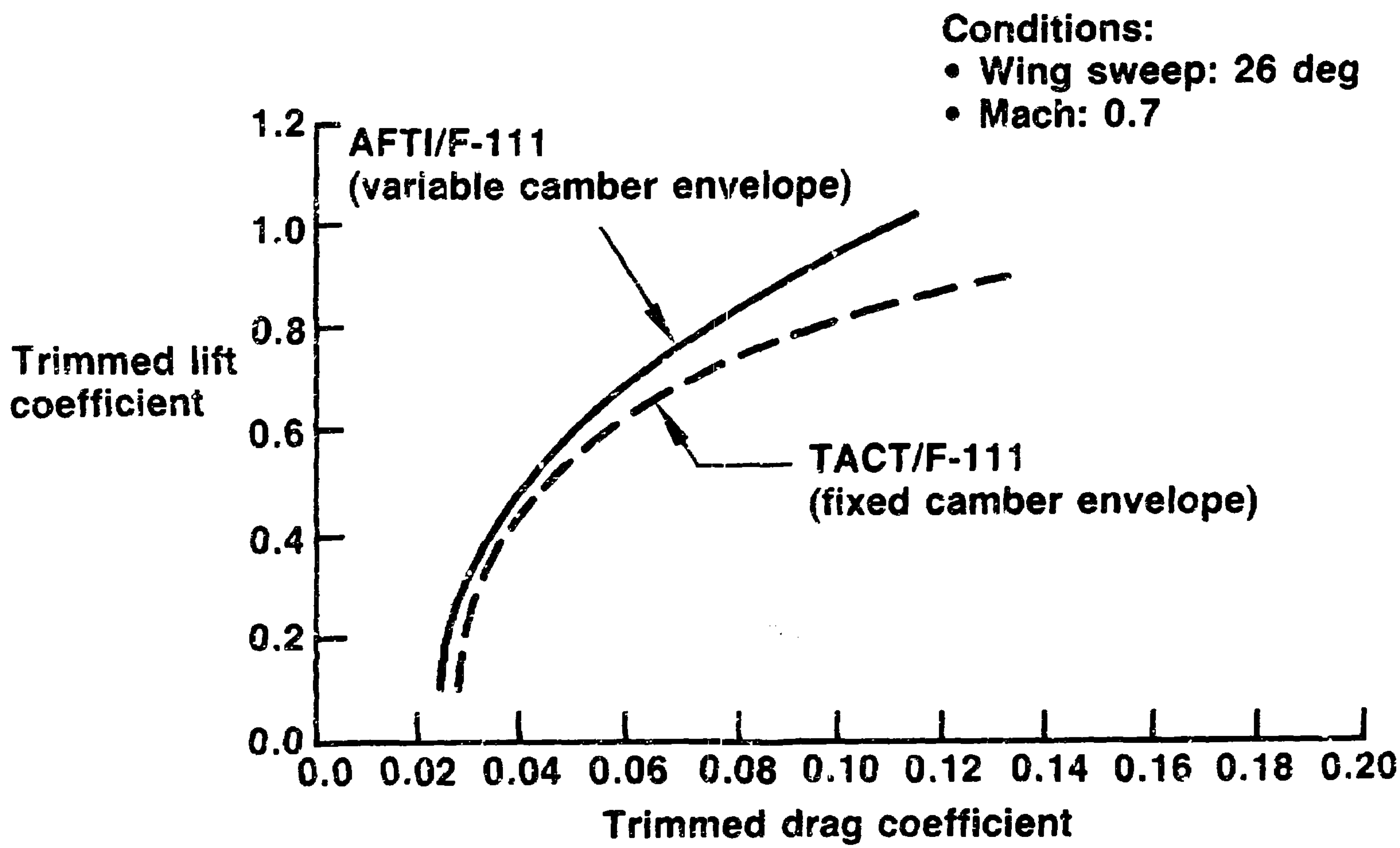
## FLAP END SEAL



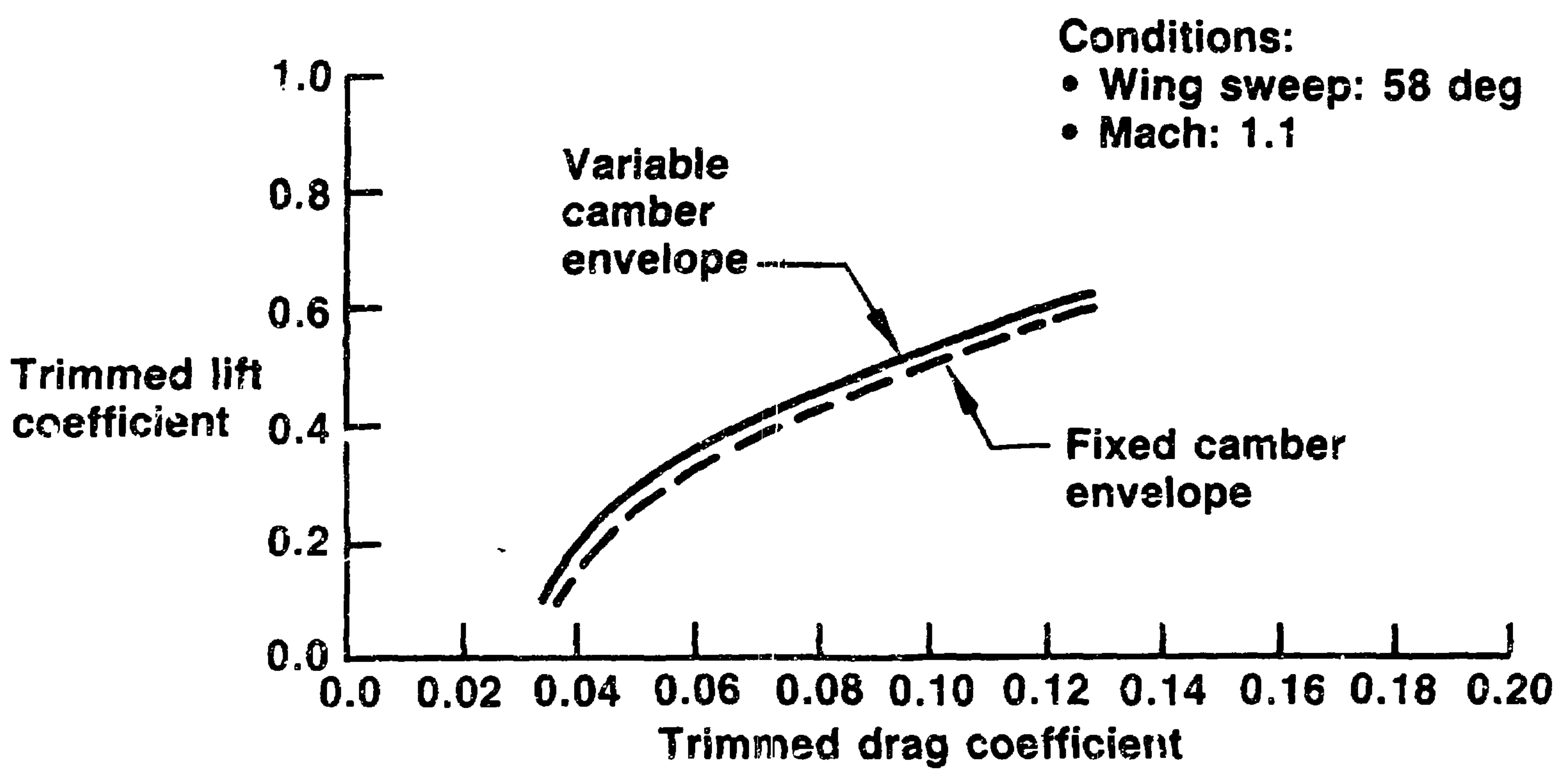
## FULL SCALE LEADING AND TRAILING EDGE FLAP TEST

- VERIFIED FUNCTION
- VERIFIED STATIC LOAD CAPABILITY
- VERIFIED CYCLIC CAPABILITY
- VERIFIED REQUIRED RATE UNDER LOAD
- VERIFIED TRAILING EDGE UP STOP DESIGN
- IDENTIFIED PROBLEM AREAS EARLY

# Variable Camber Benefits—Flight Test Data



# Variable Camber at Supersonic Speeds—Flight Test Data



# Design Considerations

- Mission Adaptive Wing design solutions will vary depending upon overall airplane system requirements
  - Simple flap
  - Smooth variable camber
  - Combinations of smooth variable camber and slotted flap
- An Automatic Flight Control System for operating modes is desirable in all cases to avoid adding to pilot workload

# Conclusions

- Feasibility of MAW concept has been demonstrated on a full scale, tactical airplane

- Predicted variable camber performance levels have been matched or exceeded in flight test

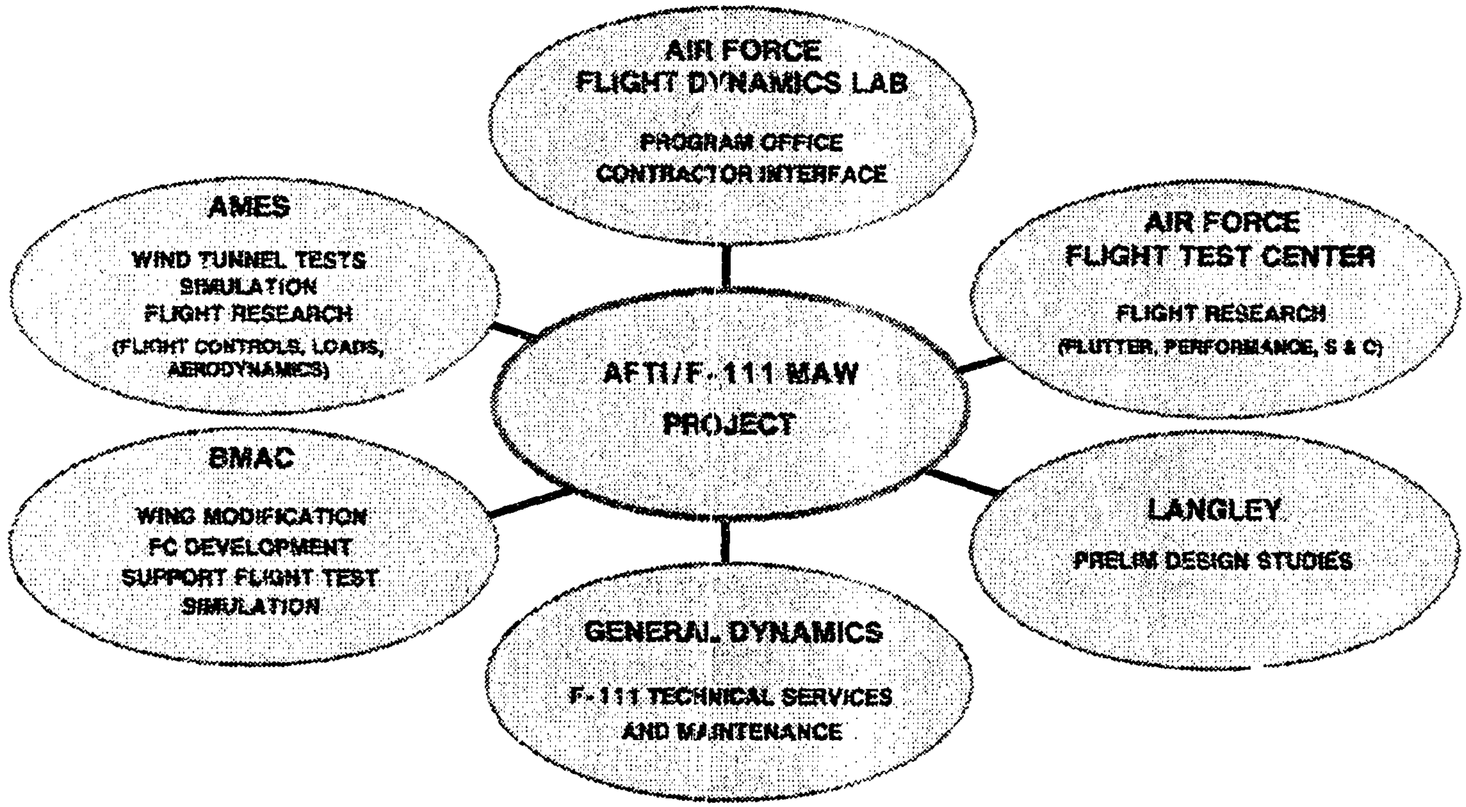
ATTACHT 3

# FLIGHT TEST OVERVIEW


**LOUIS L. STEERS**

**NASA AMES-DRYDEN PROJECT MANAGER**

# PARTICIPANTS



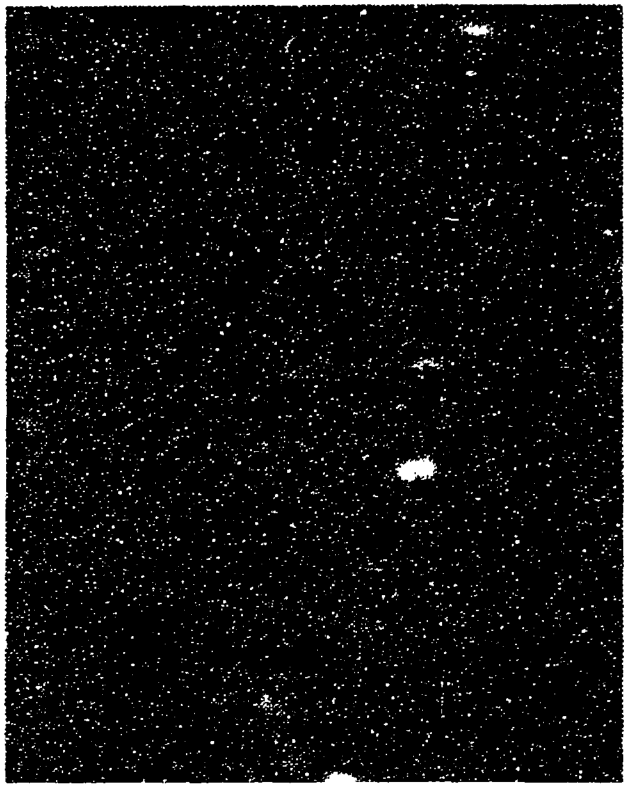
# ORGANIZATION

- MEMORANDUM OF AGREEMENT (AFFDL, AFFTC, NASA-AMES DRYDEN)

| AMES DRYDEN FLIGHT RESEARCH FACILITY | AIR FORCE FLIGHT TEST CENTER |
|---|---|
| • FLIGHT SAFETY | • FLUTTER |
| • FLIGHT EXPERIMENTS | • PERFORMANCE |
| • FLIGHT PLANNING | • ASSIST FLIGHT PLANNING STABILITY AND CONTROL |
| • DATA ACQUISITION | • HANDLING QUALITIES |
| • VEHICLE MAINTENANCE | • PROVIDE FLT TEST PILOTS |
| • PROVIDE RESEARCH PILOTS | |

C3026.057

# PROGRAM OBJECTIVES



- DETERMINE THE AERODYNAMIC PERFORMANCE IMPROVEMENTS OF A SMOOTH VARIABLE- - CAMBER AIRFOIL
- DEVELOP A DATA BASE FOR TRANSITION OF TECHNOLOGY TO FUTURE AIRPLANES

# RESEARCH OBJECTIVES
## (AFFTC AND NASA)

- OBTAIN AIRCRAFT LIFT AND DRAG DATA TO EVALUATE AIRCRAFT PERFORMANCE IN COMPARISON TO F-111A/TACT CONFIGURATION
- EVALUATE AIRFOIL CHARACTERISTICS USING WING PRESSURE DISTRIBUTIONS AND COMPUTATIONAL FLUID DYNAMICS
- OBTAIN AERODYNAMIC LOADS DATA ON SYSTEM LINKAGES, FLEXIBLE PANELS, WINGBOX, AND WING CARRY-THROUGH STRUCTURE
- OBTAIN STABILITY AND CONTROL DERIVATIVE DATA TO EVALUATE AERODYNAMIC EFFECTS OF MAW

C3026.056

# MAW DESIGN APPROACH

MAW FLIGHT CONTROL ELECTRONICS
- DUAL DIGITAL
- DUAL ANALOG

EXISTING TACT/F-111 WING BOX

3 SEGMENT FLEXIBLE TRAILING EDGE

SINGLE SEGMENT FLEXIBLE LEADING EDGE

EXISTING F-111 PITCH CONTROL SYSTEM

ADVANCED SUPERCRITICAL AIRFOIL

F-111 -- A VERSATILE TEST BED

## AFTI/F-111

F2516.005

(4) PHOTO

# ACCOMPLISHMENTS

- 44 FLIGHTS FLOWN
- 105 FLIGHT HOURS ON MAW SYSTEM
- FLIGHT ENVELOPE CLEARED TO MACH 1.3
- AUTOMATIC FLIGHT CONTROLS SYSTEM INTEGRATED

## MANUAL FLIGHT CONTROL SYSTEM - FLIGHT STATUS

- PRESSURE DISTRIBUTION
- STABILITY AND CONTROL
- BUFFET
- PERFORMANCE FLIGHT TEST
- AERODYNAMIC LOADS

## AUTOMATIC FLIGHT CONTROL SYSTEM - FLIGHT STATUS

- CRUISE CAMBER CONTROL (CCC)
- MANEUVER CAMBER CONTROL (MCC)
- MANEUVER LOAD CONTROL (MLC)
- MANEUVER ENHANCEMENT / GUST ALLEVIATION
- MODE COMBINATIONS

## SESSION II

## MANUAL FLIGHT CONTROL SYSTEM FLIGHT TEST RESULTS

11817.001

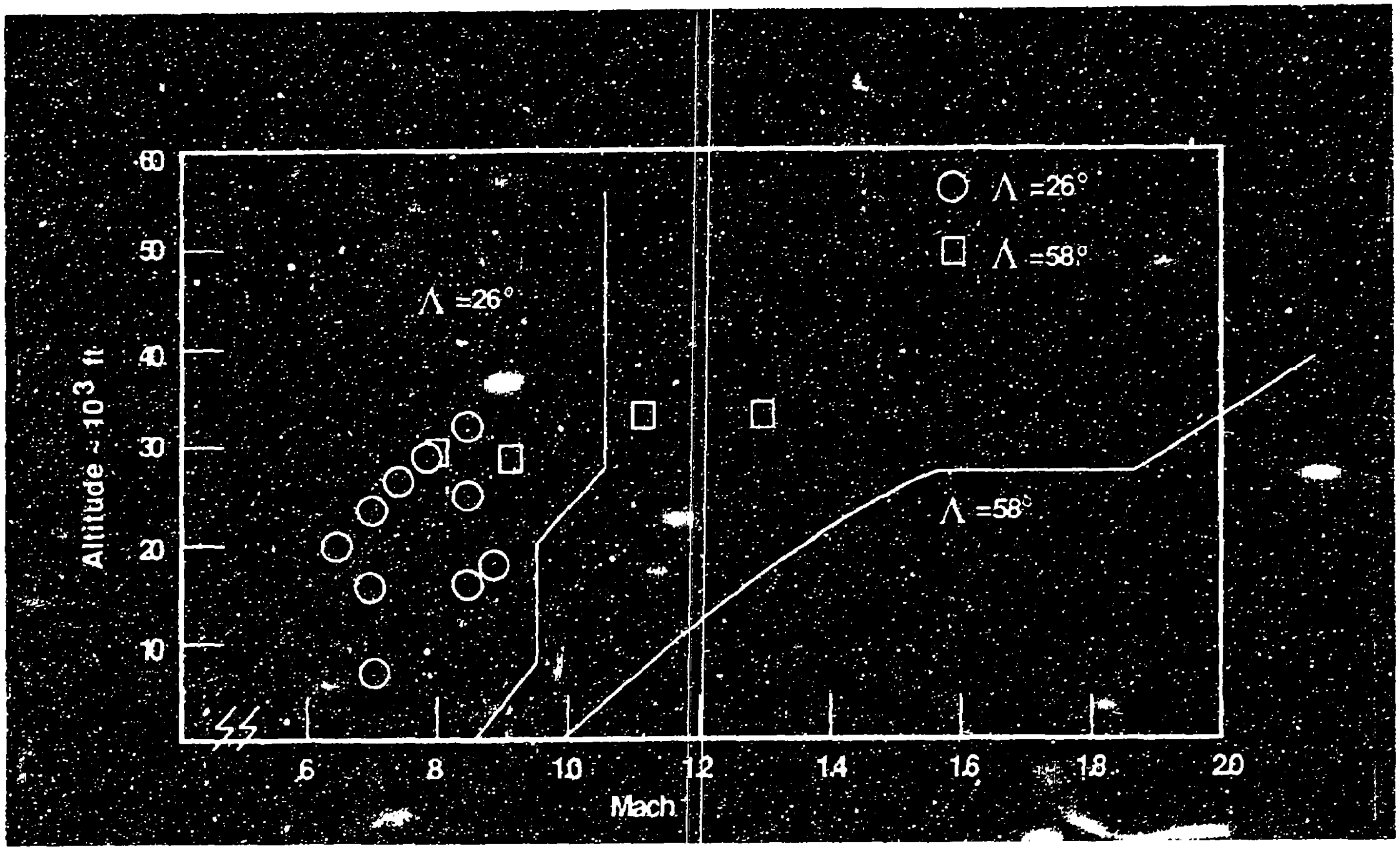

AFWAL
AFFTC
USAF
NASA
DFRF
LaRC
MISSION ADAPTIVE WING
PERFORMANCE FLIGHT TEST

# TEST OBJECTIVES

- DETERMINE TRIMMED AIRCRAFT DRAG
- ASSESS ACCURACY OF WIND TUNNEL AND ANALYTICAL DRAG
- PROVIDE DATA FOR MISSION ANALYSIS

C3026.004

# PERFORMANCE FLIGHT TEST CONDITIONS




A1108.W11

# TEST APPROACH

$\Lambda$ 26°

| TEST CAMBERS | $\bar{Q}$ 300 - 600 PSF |
|---|---|
| 0/2 | |
| 5/2 | |
| 5/6 | |
| 5/10 | |

$\Lambda$ 58°

| TEST CAMBERS | $\bar{Q}$ 300 - 700 PSF |
|---|---|
| 0/2 | |
| 5/6 | |
| 10/6 | |
| 0/-1 | 25 FLIGHTS |
| 10/-1 | 13 PERFORMANCE FLIGHTS |
| 10/2 | |

C3026.033

# THRUST COMPUTATION

- PRATT & WHITNEY PRESSURE AREA METHOD

  $F_{i_{pri}} = \psi \, P_a \, A_j$

  $\psi$ = GROSS THRUST PARAMETER

  $P_a$ = ATMOSPHERIC PRESSURE

  $C_{gp}$ = GROSS THRUST COEFFICIENT

- $F_{g_{pri}} = \psi \, P_a \, A_j \, C_{gp}$

  $A_j$ = NOZZLE AREA

C3026.008

# DRAG COMPUTATION

WHERE:

$F_{g_a}$ = ADJUSTED GROSS THRUST

$\Delta F_{N_{AB}}$ = AFTER BODY EFFECTS

$F_e$ = RAM DRAG

$i_F$ = ENGINE INCIDENCE ANGLE

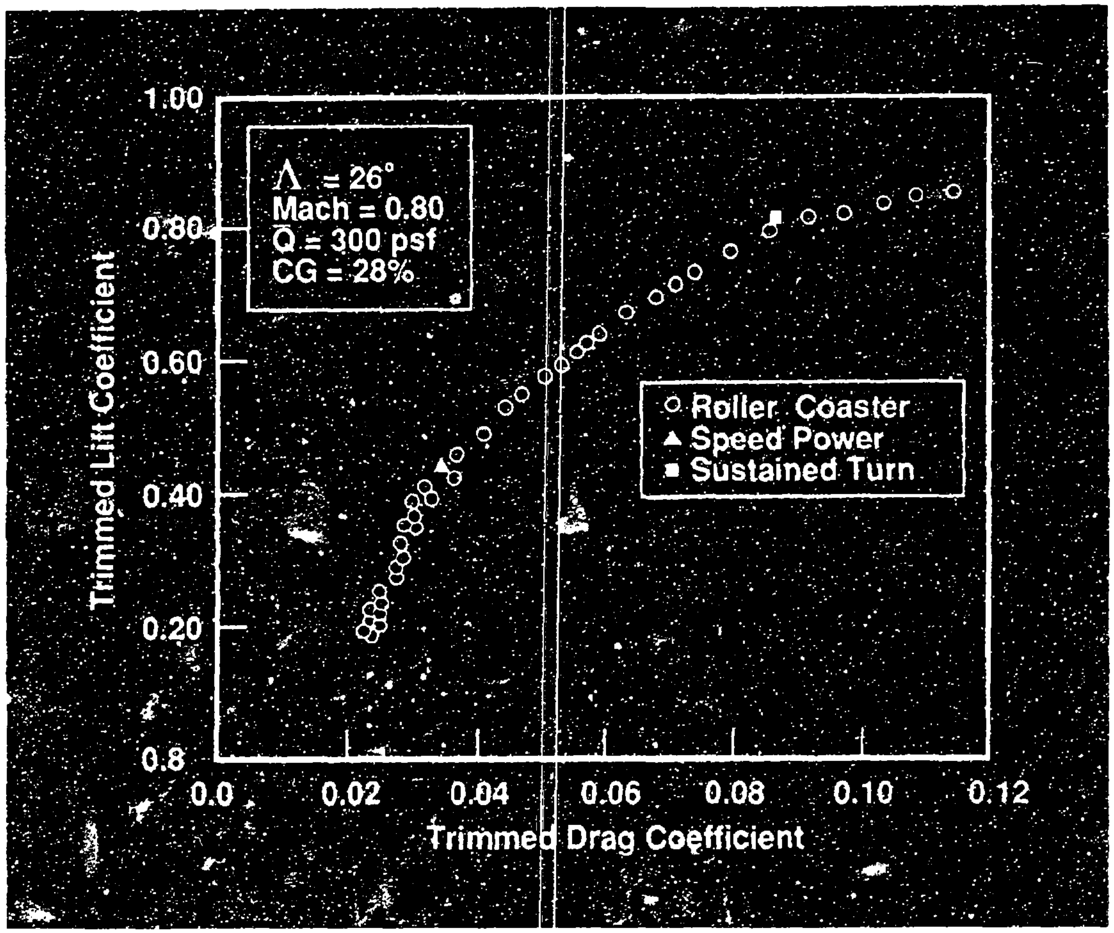
$$F_{g_a} = F_g + \Delta F_{N_{AB}}$$

$$C_{L_t} = \frac{n_{z_w} W - F_{g_a} \sin(\alpha - i_F)}{\bar{q}S}$$

$$C_{D_t} = \frac{F_{g_a} \cos(\alpha - i_F) - F_e - n_{x_w} W}{\bar{q}S}$$

C3026.013

# DRAG POLAR FLIGHT DATA

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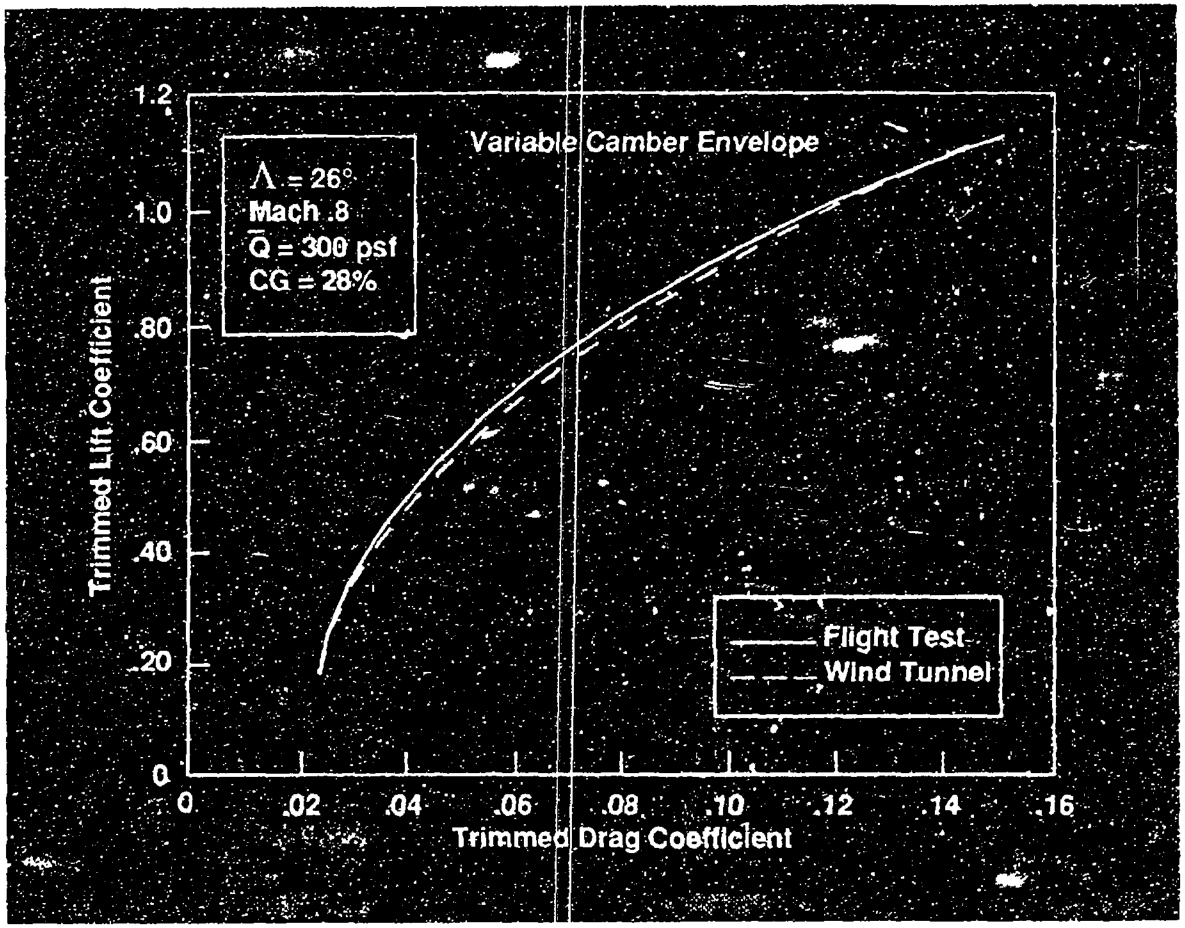
# FLIGHT TEST TO WIND TUNNEL COMPARISON - 26 DEG SWEEP

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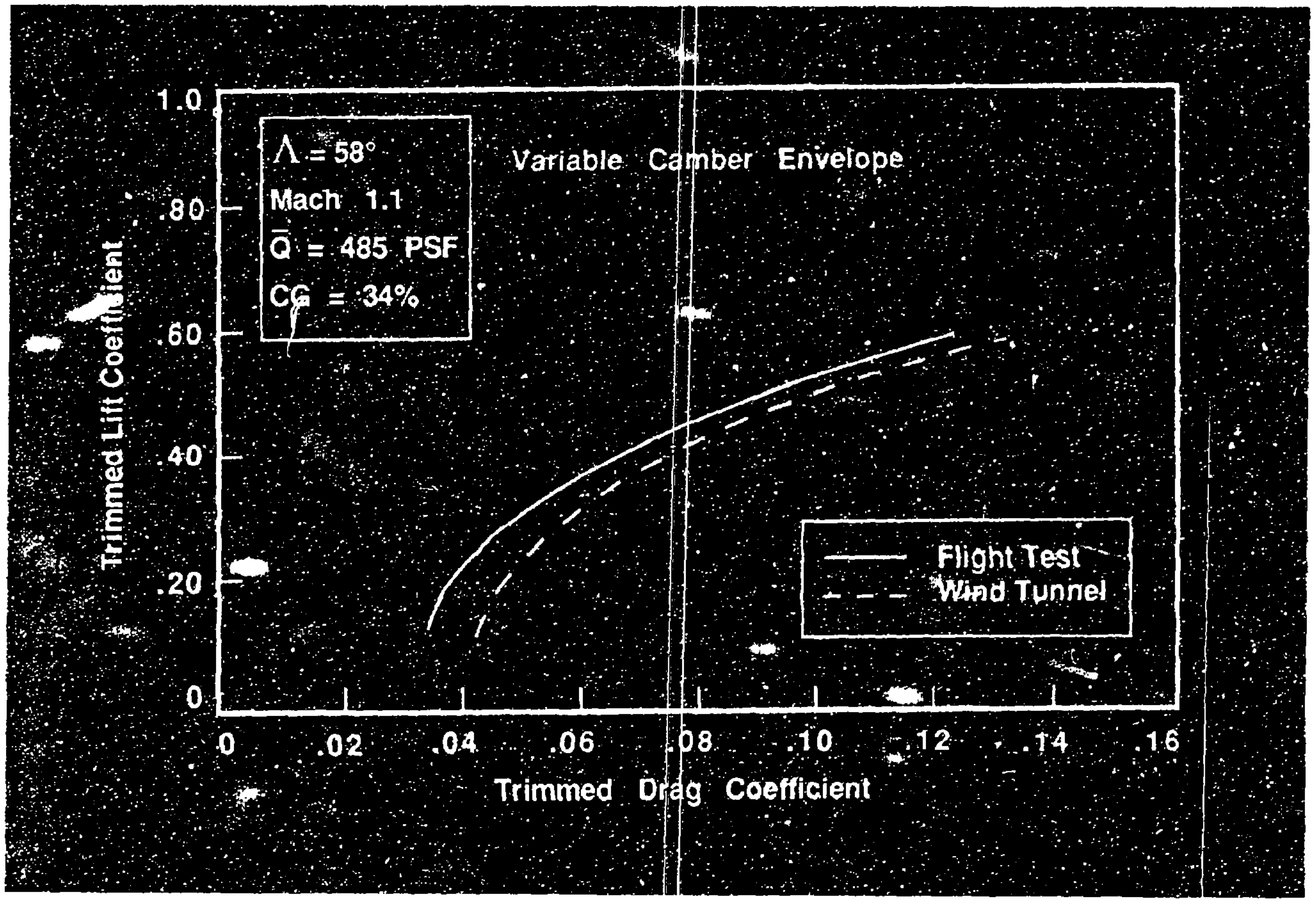


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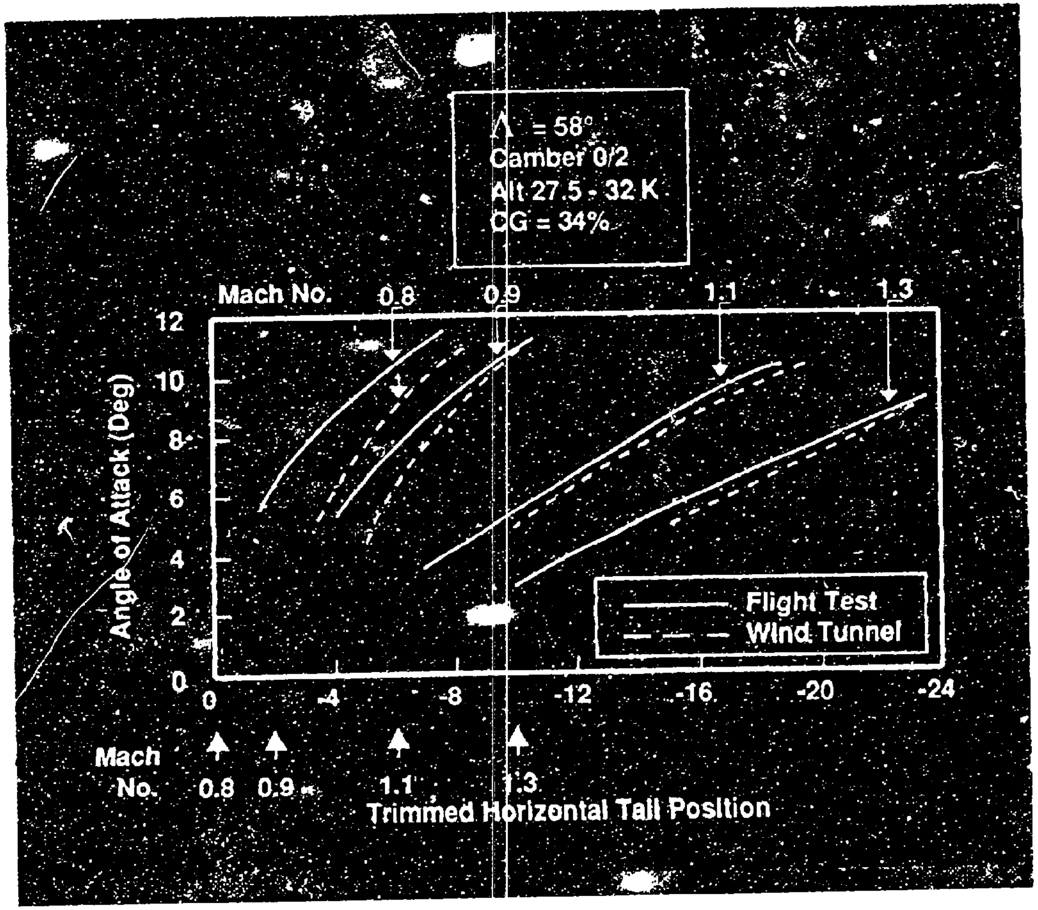
## FLIGHT TEST TO WIND TUNNEL COMPARISON - TRIMMED HORIZONTAL TAIL

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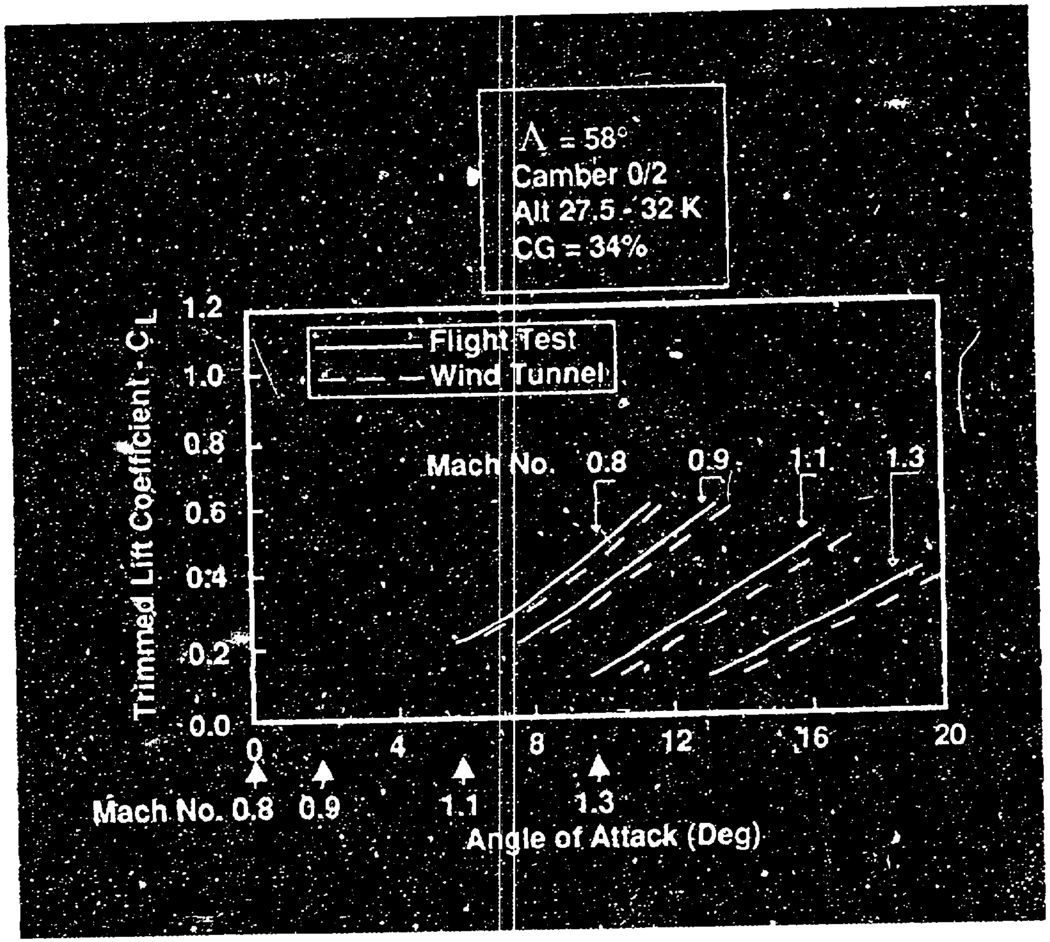
# FLIGHT TEST TO WIND TUNNEL COMPARISON - TRIMMED LIFT

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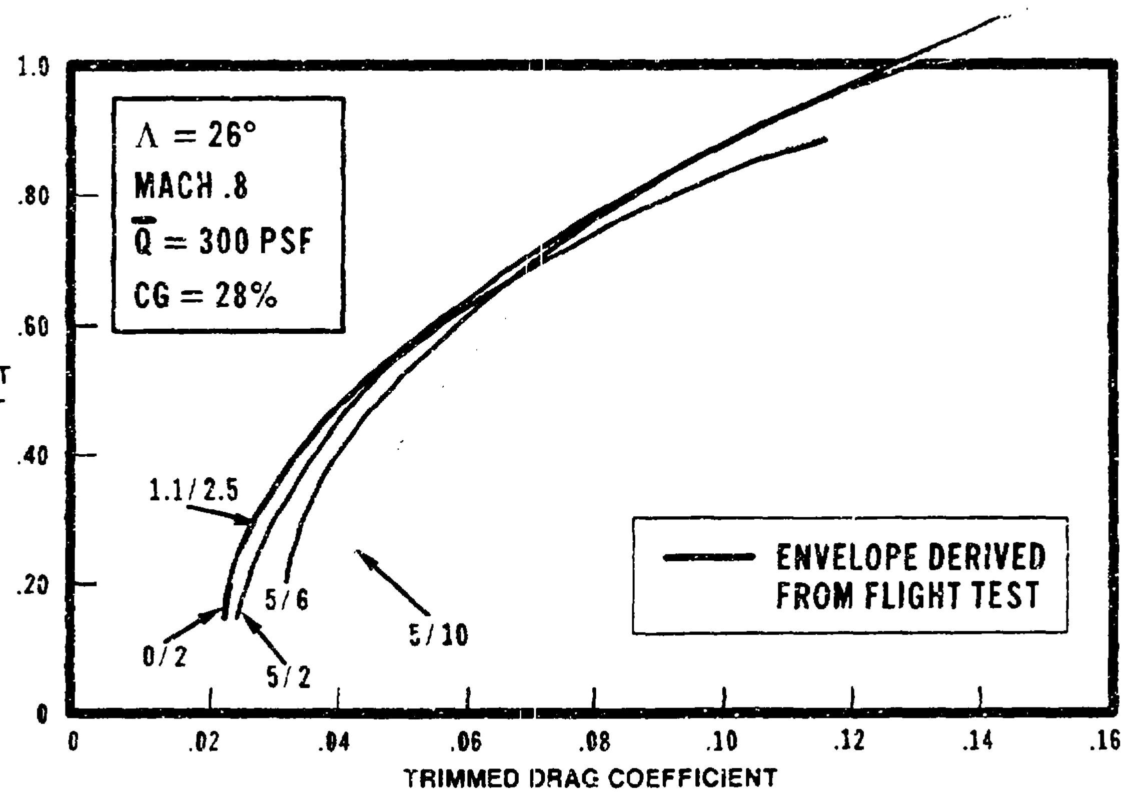
# VARIABLE CAMBER ENVELOPE GENERATION

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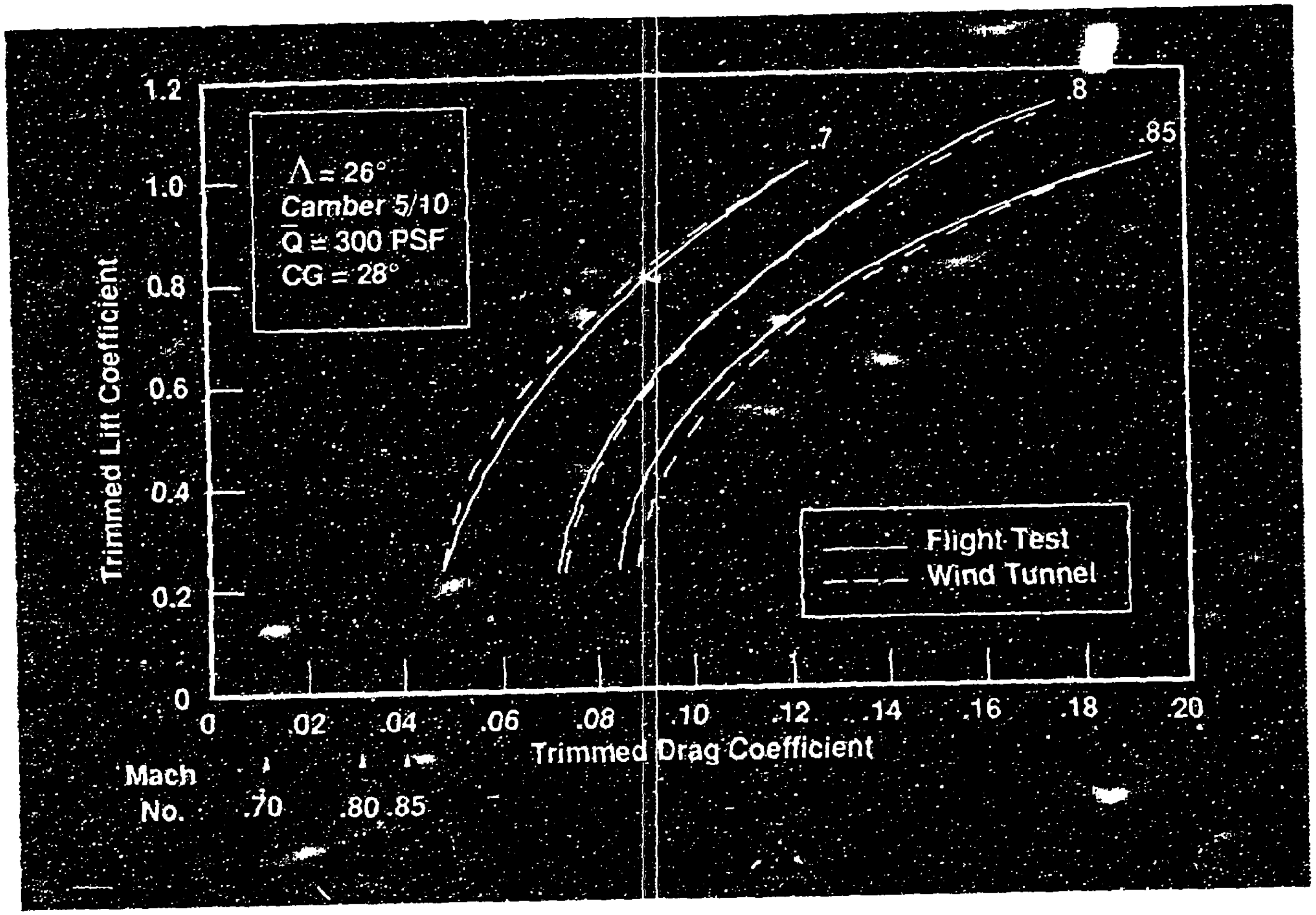
# DRAG POLAR COMPARISON
# 26 DEG SWEEP

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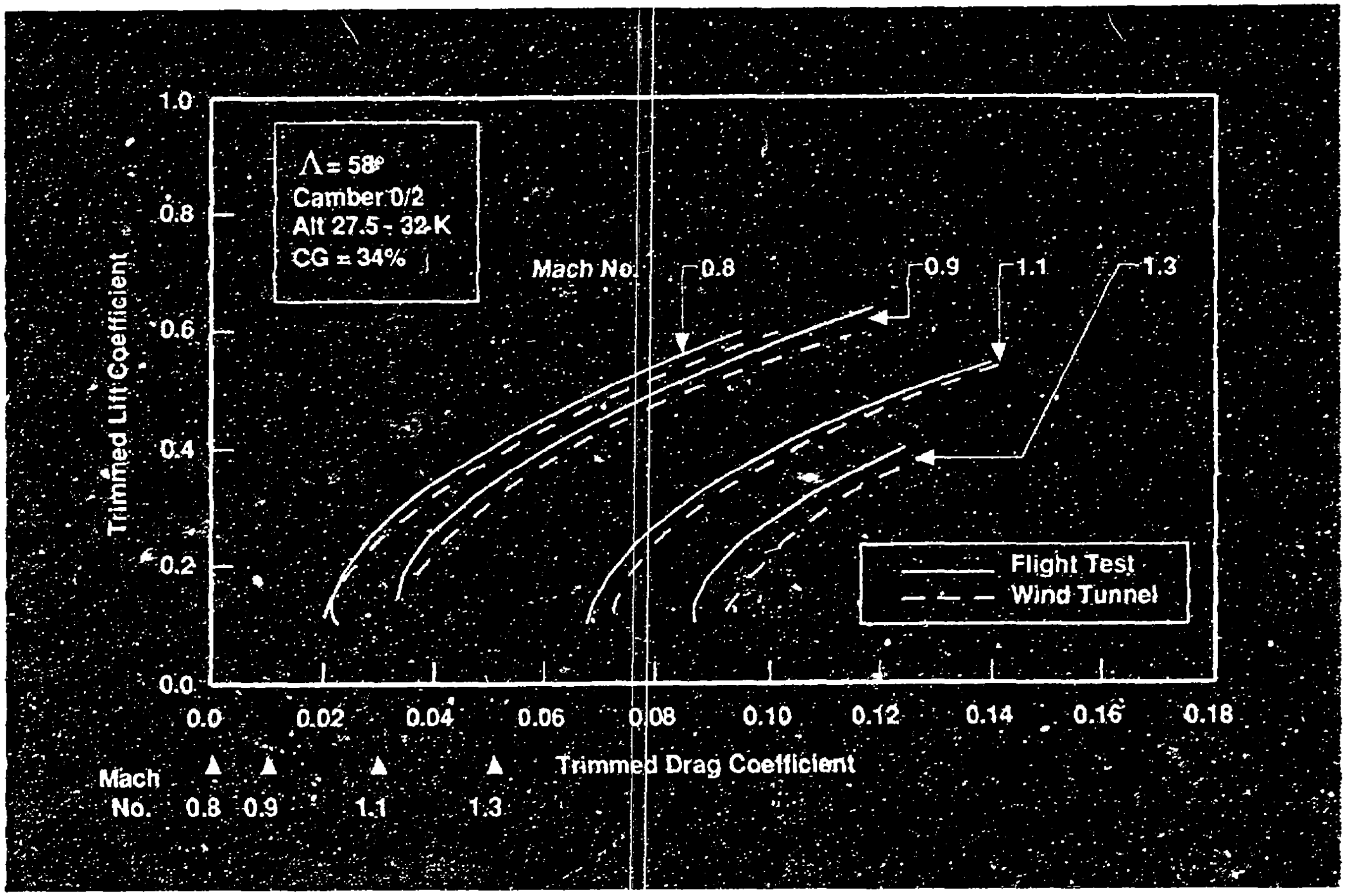
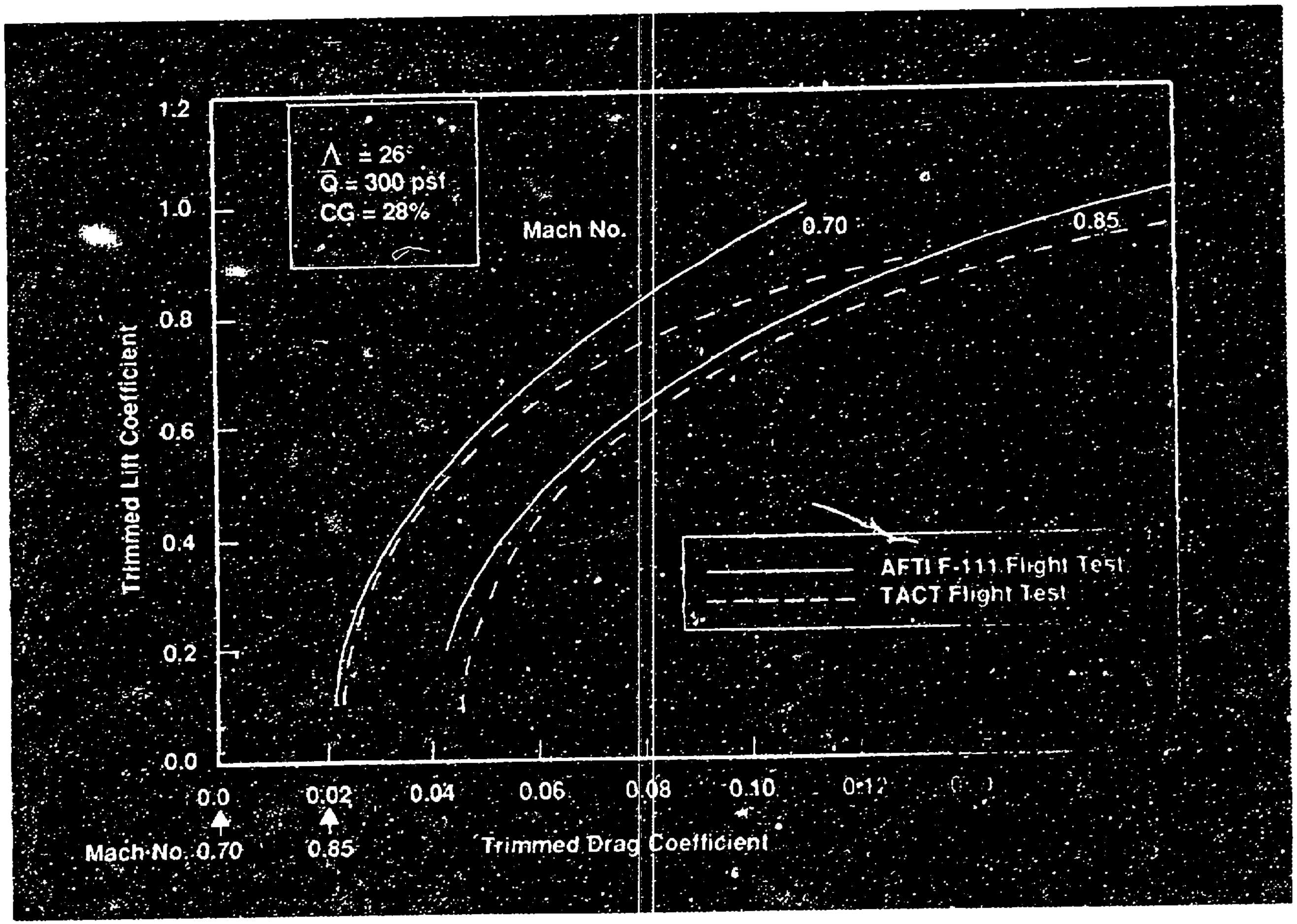
# DRAG POLAR COMPARISON
# 58 DEG SWEEP




A1108.W04

# AFTI TO TACT FLIGHT TEST COMPARISON - DRAG POLAR




A1108.W06

# CONCLUSIONS

- DATA QUALITY $\pm$ 30 COUNTS
- GOOD AGREEMENT WITH WIND TUNNEL
- BENEFITS OVER TACT
- SUITABLE FOR MISSION ANALYSIS

C3026.034

C3026.054

6510TW/TER

LFB

# *AFTI/F-111 MISSION ADAPTIVE WING*

# *STABILITY AND CONTROL TESTING*

C3026.054

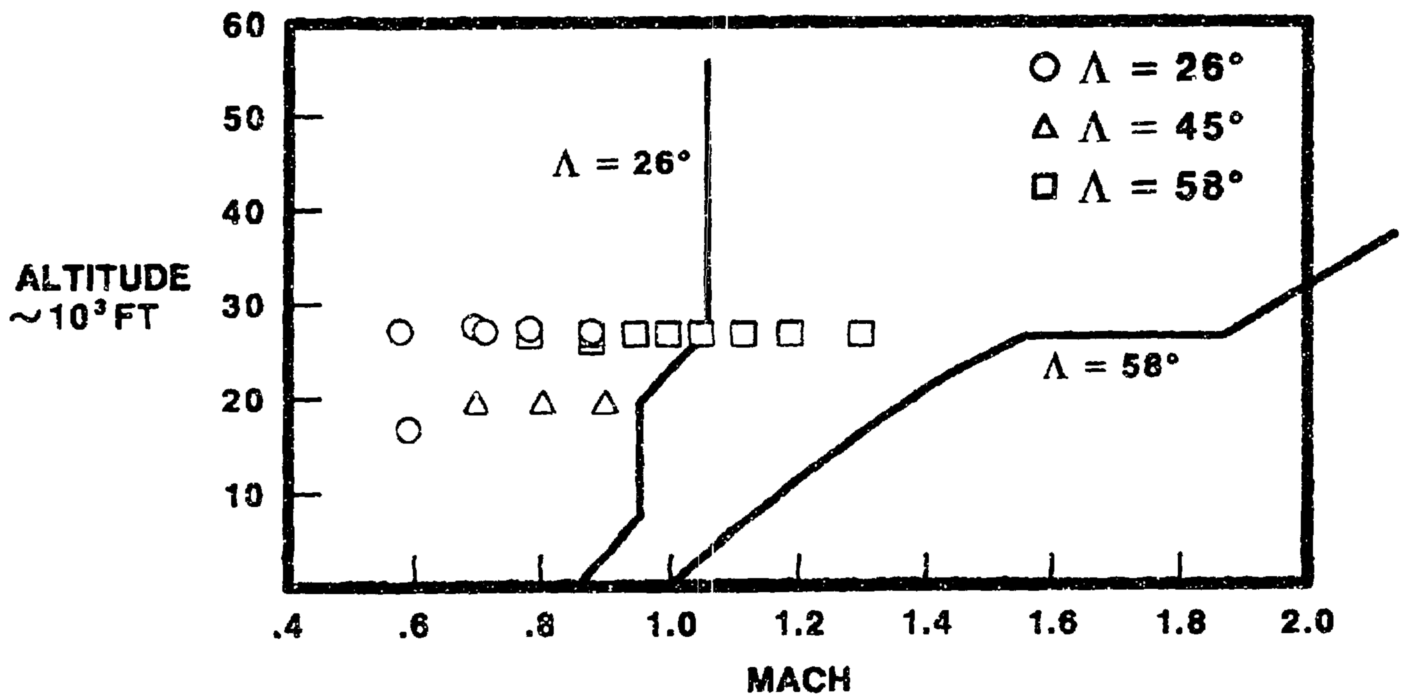
# OBJECTIVES

- ENVELOPE CLEARANCE
  - CAMBER
  - WING SWEEP
  - ANGLE OF ATTACK
- AERODYNAMIC INVESTIGATION
  - CAMBER EFFECTS
  - FLEXIBILITY

C3026.091

# TEST APPROACH

## TEST ENVELOPE




C3026.045

# TEST CONFIGURATION

## LEADING EDGE / TRAILING EDGE CAMBER

| $\Lambda = 26°$ | |
|---|---|
| 0/2 | 20/18 |
| 0/10 | 15/10 |
| 5/2 | 20/15 |
| 5/10 | |

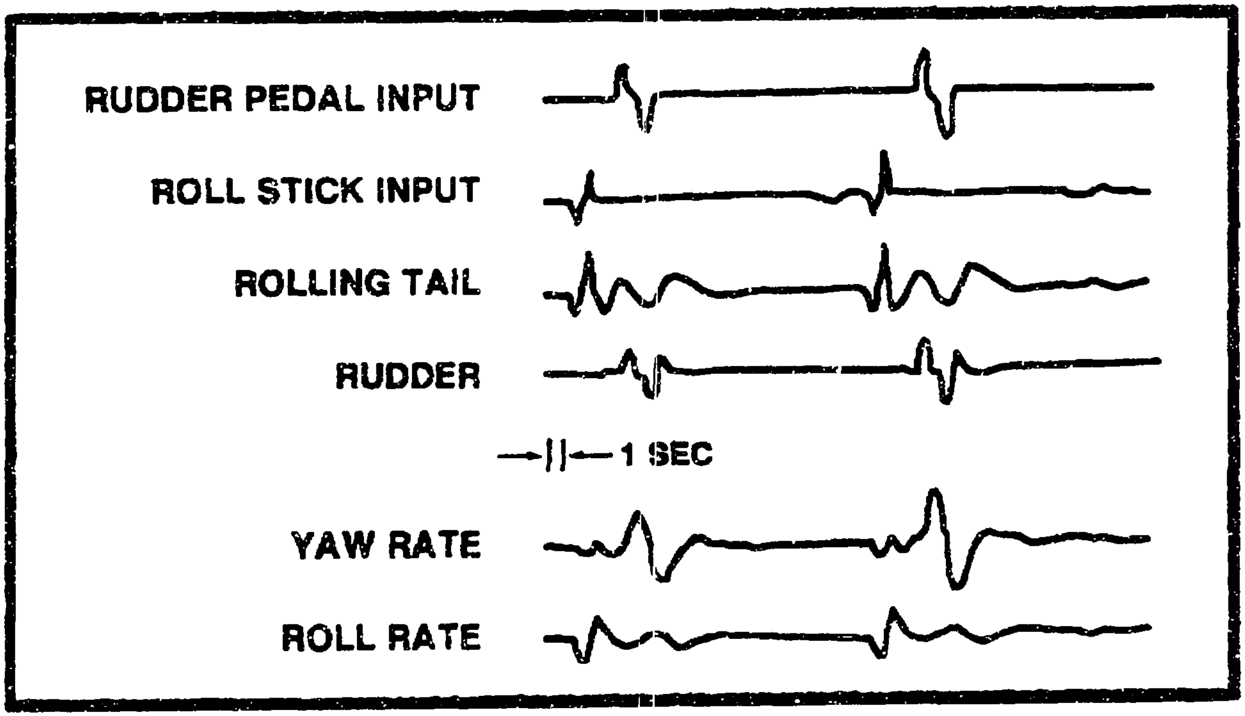
| $\Lambda = 45°$ |
|---|
| 0/2 |
| 0/4 |
| 0/6 |

| $\Lambda = 58°$ | |
|---|---|
| 0/-1 | 10/6 |
| 0/2 | |
| 5/6 | |
| 10/2 | |

C3026.055

# TYPICAL LATERAL DIRECTIONAL DOUBLET

## STABILITY AUGMENTATION ON

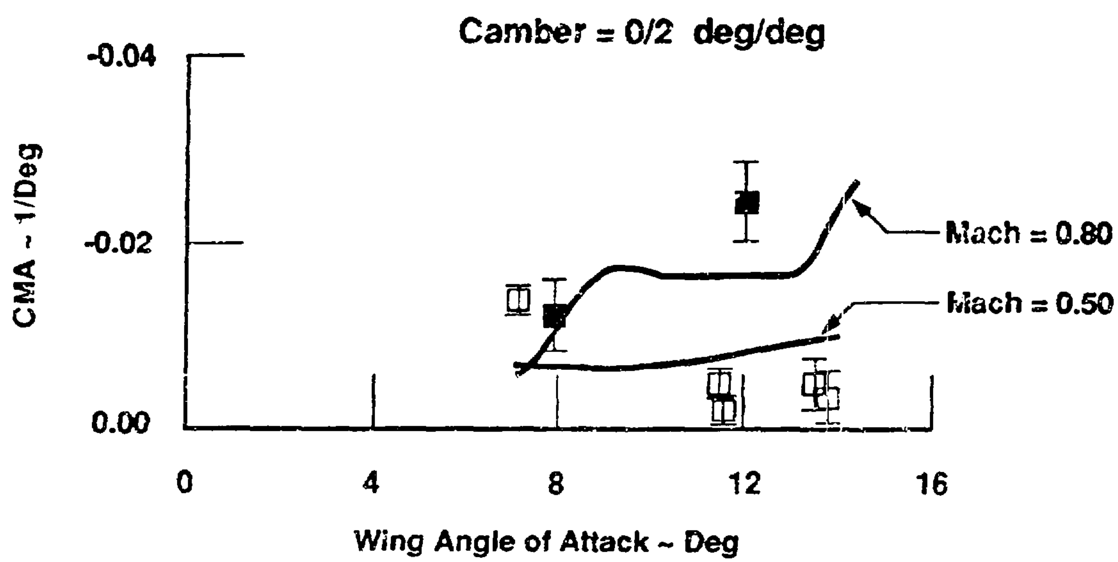



C3026.037

# Stability and Control Parameter Identification

## 26 Degree Wing Sweep
## Longitudinal Body Axis

CG = 28 PCT MAC
Q = 125 - 325 PSF




NOTE: Fairings represent contractor wind tunnel analysis results

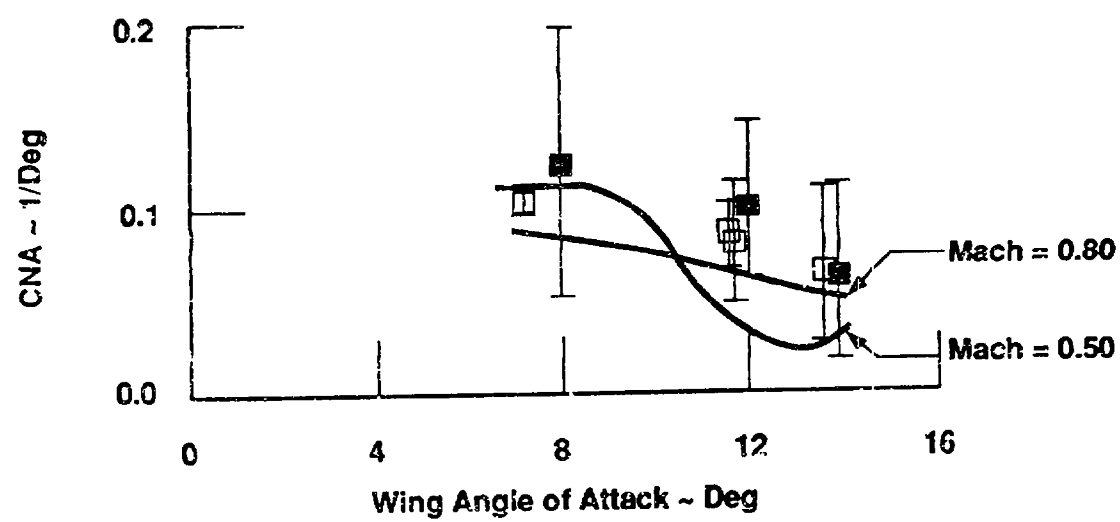
Shaded symbols denote Mach number > 0.70

# Stability and Control Parameter Identification

## 26 Degree Wing Sweep
## Longitudinal Body Axis

CG = 28 PCT MAC
Q = 125 - 325 PSF

Camber = 0/2 deg/deg



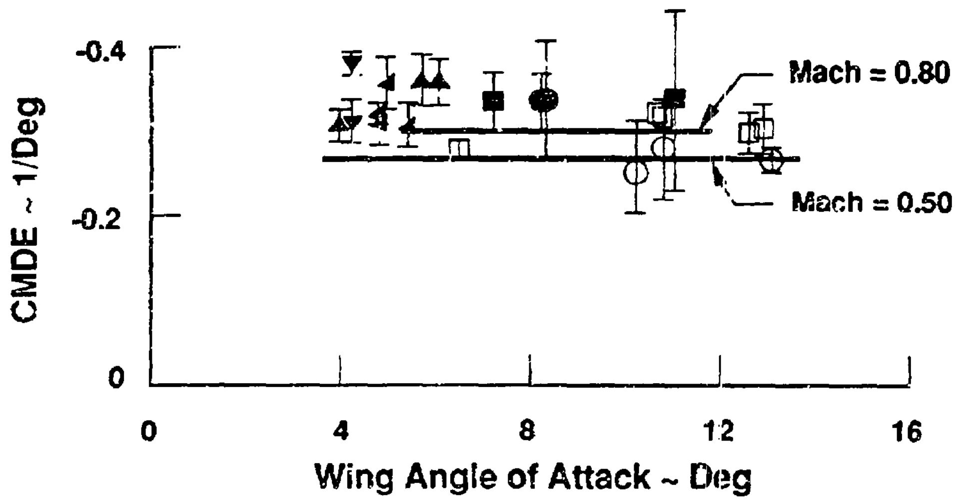

NOTE: Fairings represent contractor wind tunnel analysis results

Shaded symbols denote Mach number > 0.70

# Stability and Control Parameter Identification

**26 Degree Wing Sweep**
**Longitudinal Body Axis**

CG = 28 PCT MAC
Q = 125 - 325 PSF




| SYMBOL | CAMBER |
|---|---|
| □ | 0/2 |
| ○ | 0/10 |
| △ | 5/10 |
| ◇ | 15/10 |
| ▽ | 5/6, 3/6 |
| ◁ | 5/2, 3/2 |

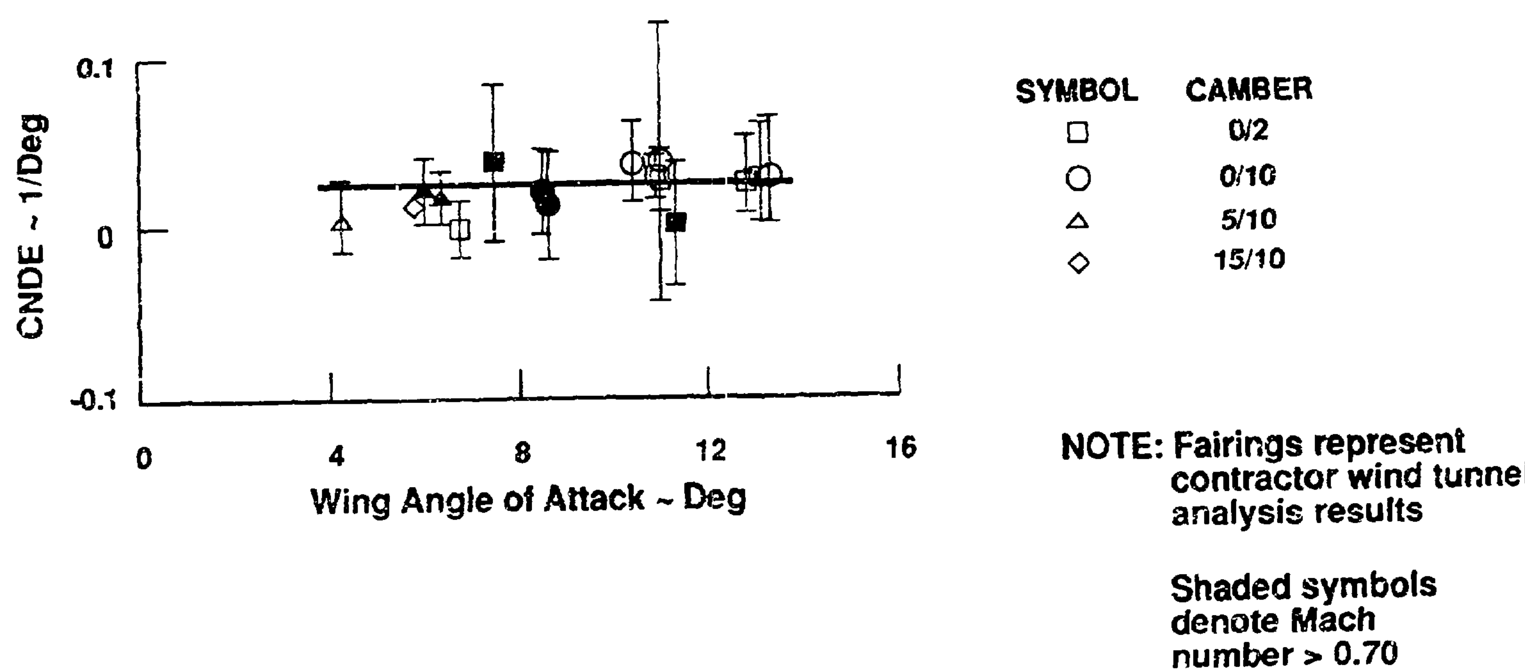
NOTE: Fairings represent contractor wind tunnel analysis results

Shaded symbols denote Mach number > 0.70

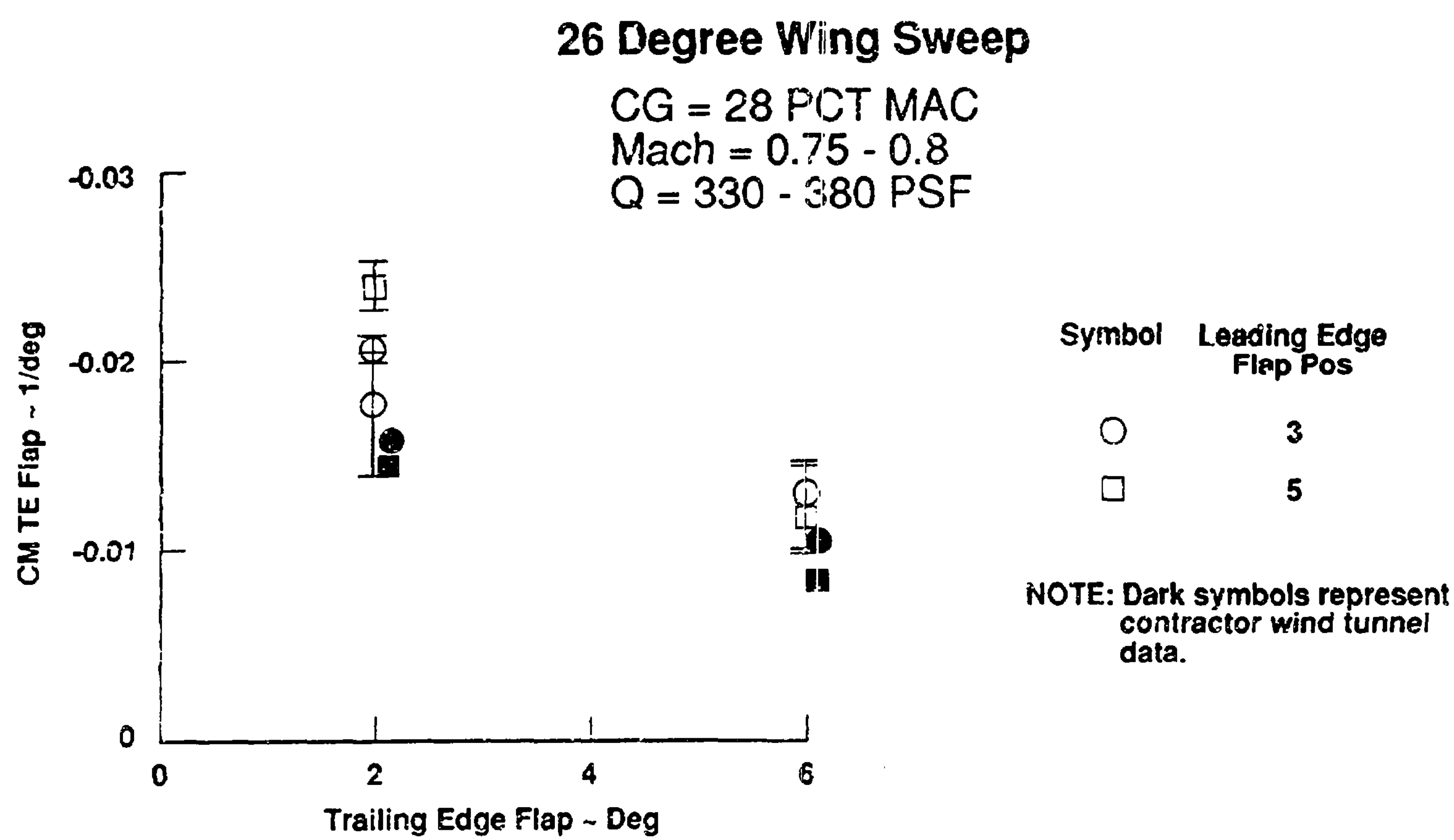
# Stability and Control Parameter Identification

**26 Degree Wing Sweep**
**Longitudinal Body Axis**

CG = 28 PCT MAC
Q = 125 - 325 PSF

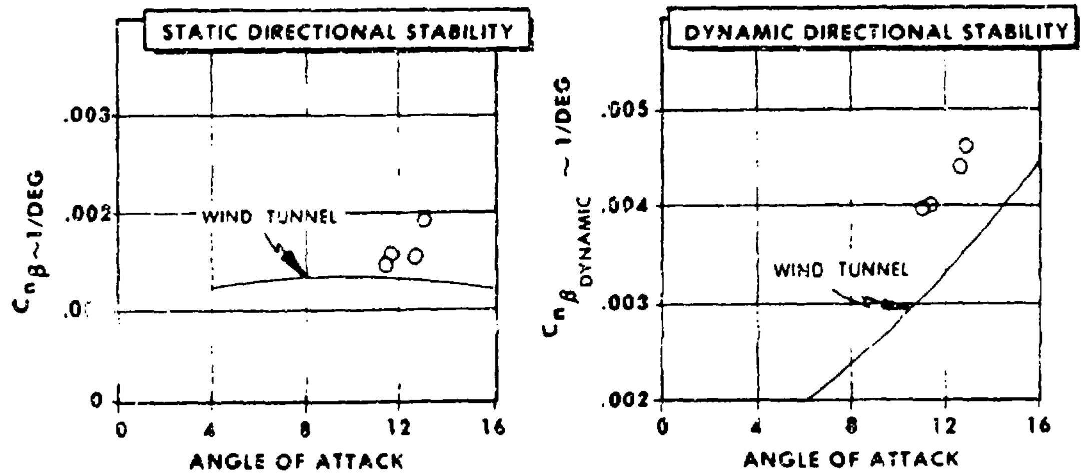


# Stability and Control Parameter Identification



# FLIGHT TEST RESULTS
## LATERAL - DIRECTIONAL

WING SWEEP: 26 DEG
MACH : $\leq .06$
CAMBER : 0/2




C3026 050

# CONCLUSIONS

- WIND TUNNEL VALIDITY
  - FAIR AGREEMENT WITH FLIGHT TEST
  - SOME DISPARITIES NOTED
- ELEVATED ANGLE OF ATTACK
  - UNCAMBERED: SIMILAR TO TACT
  - CAMBERED: LESS STABLE THAN TACT

C3026.052

# AFTI/F-111
# -Structural Loads-
# Flight Test Results

Steve Thornton
Ames Dryden Flight Research Facility

AFTI/F-111

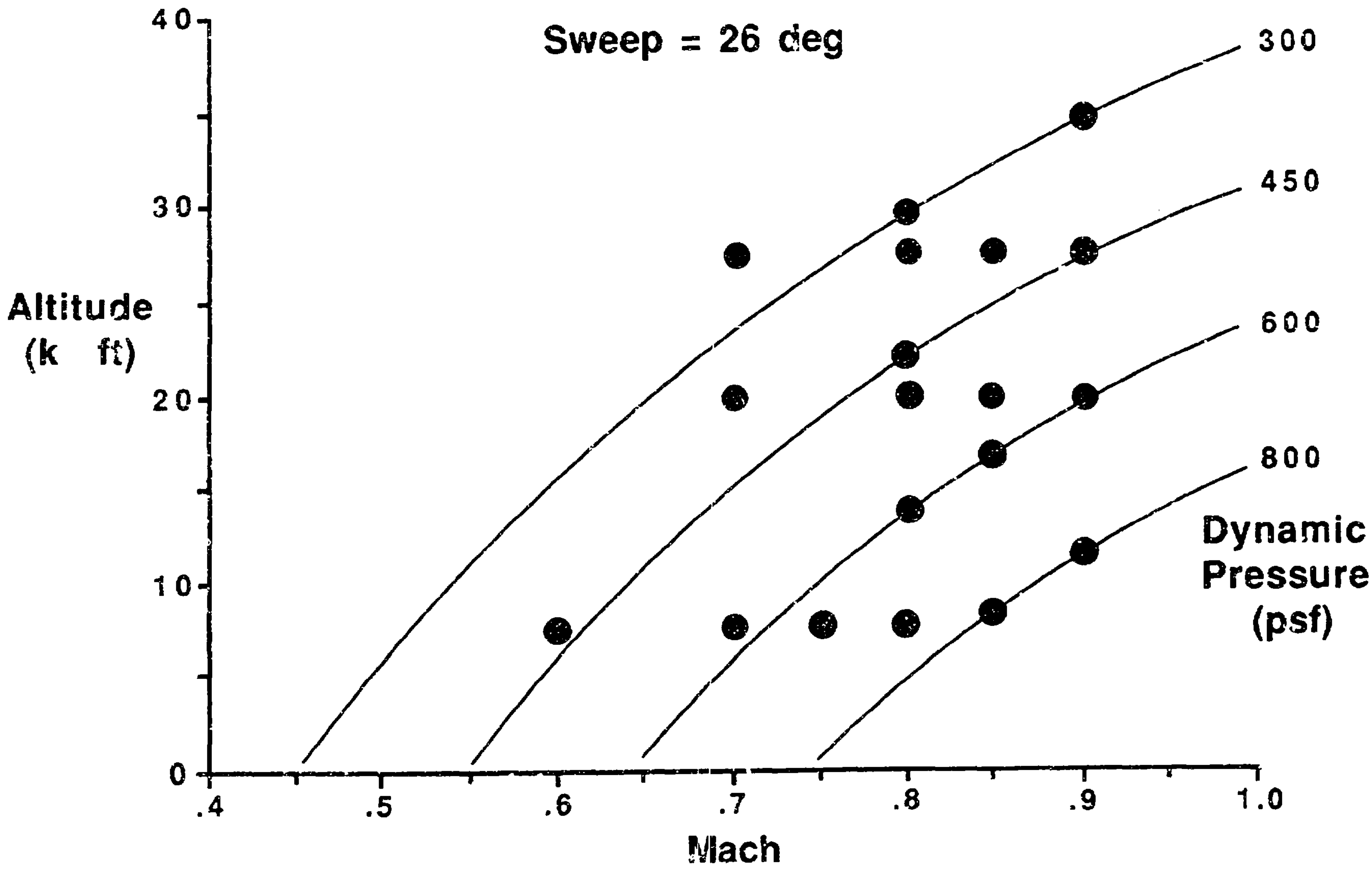
ST
6-22-88

# NASA FLIGHT LOADS PROGRAM OBJECTIVES

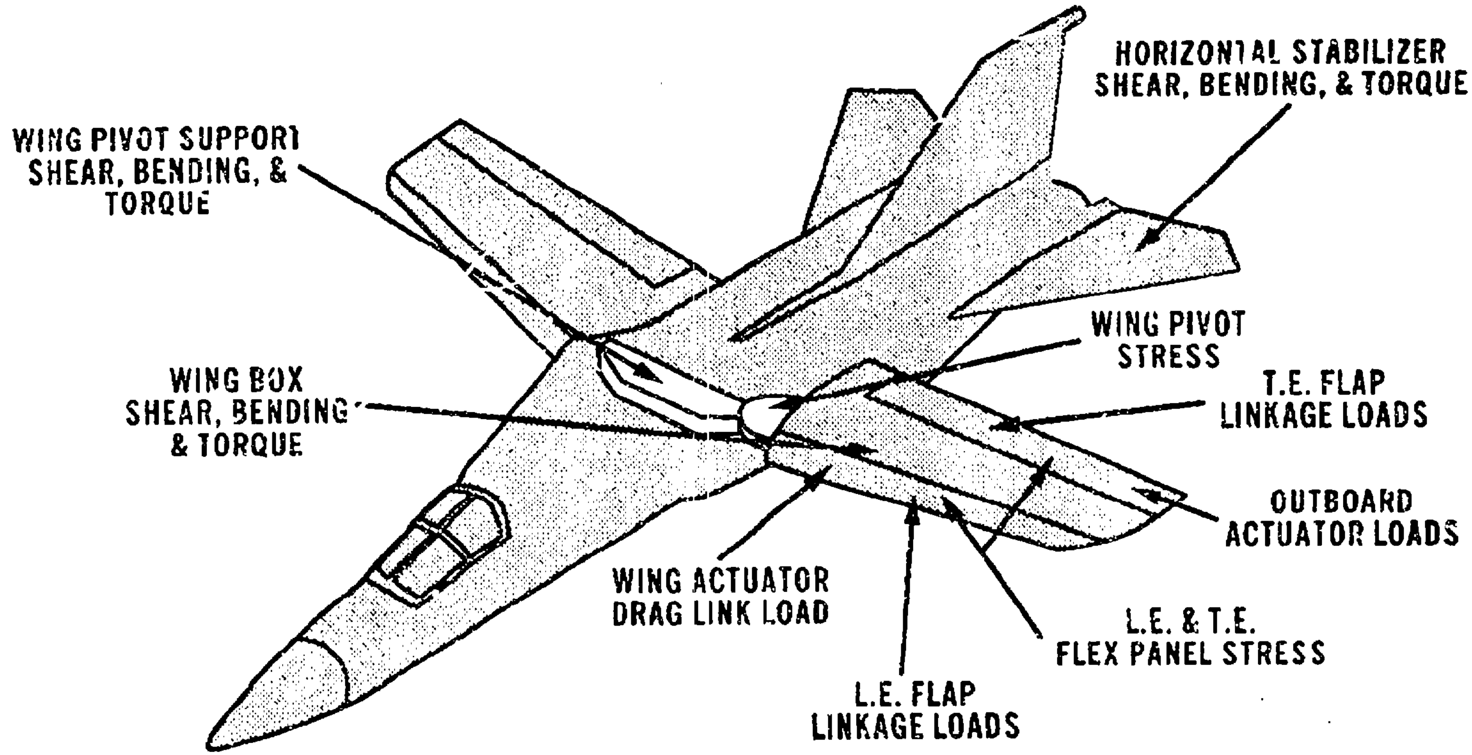
- Safety of Flight
- Loads Envelope Expansion
- Loads Measurements for NASA Flight Loads Research
- Wing Deflection Measurements supporting NASA and Air Force Aerodynamic Research

## Loads Envelope Expansion Matrix



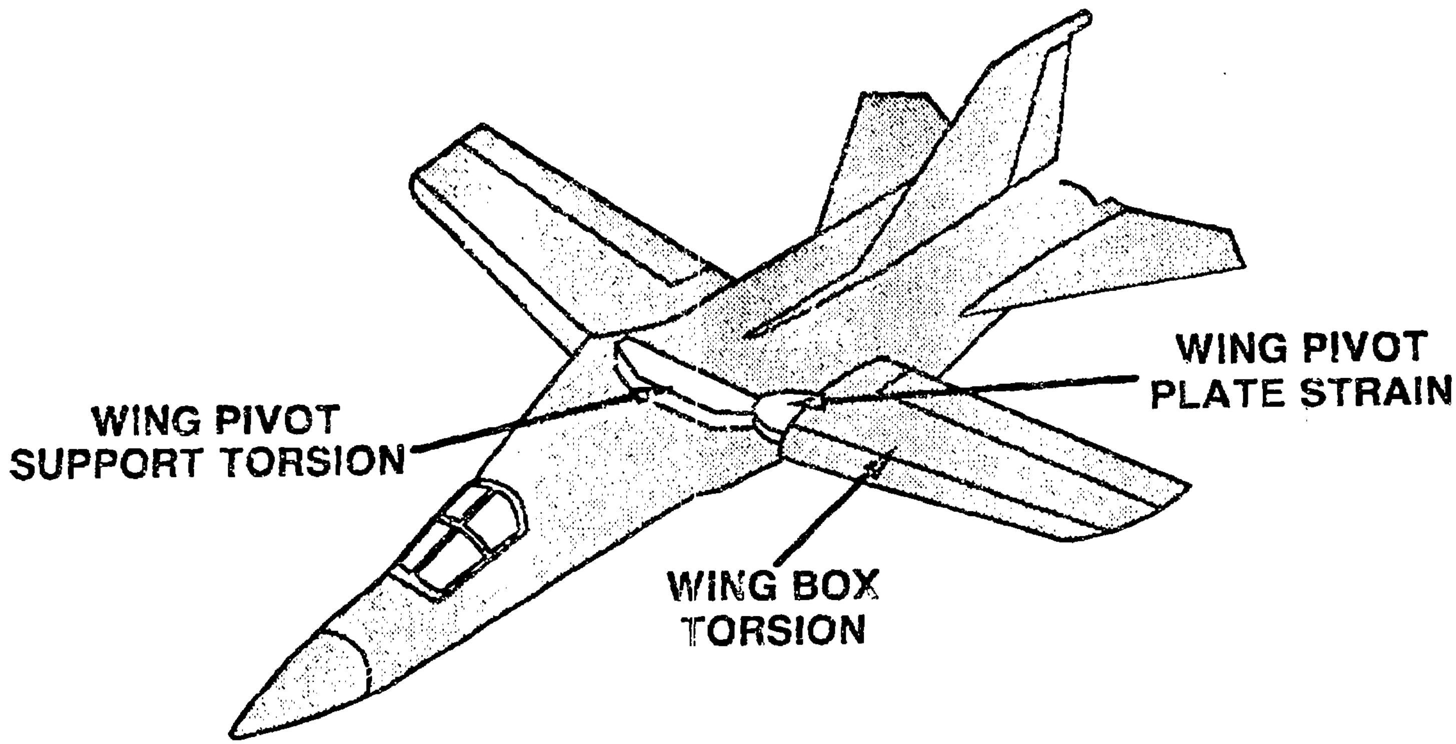


# STRAIN GAGE INSTRUMENTATION




C3026.071

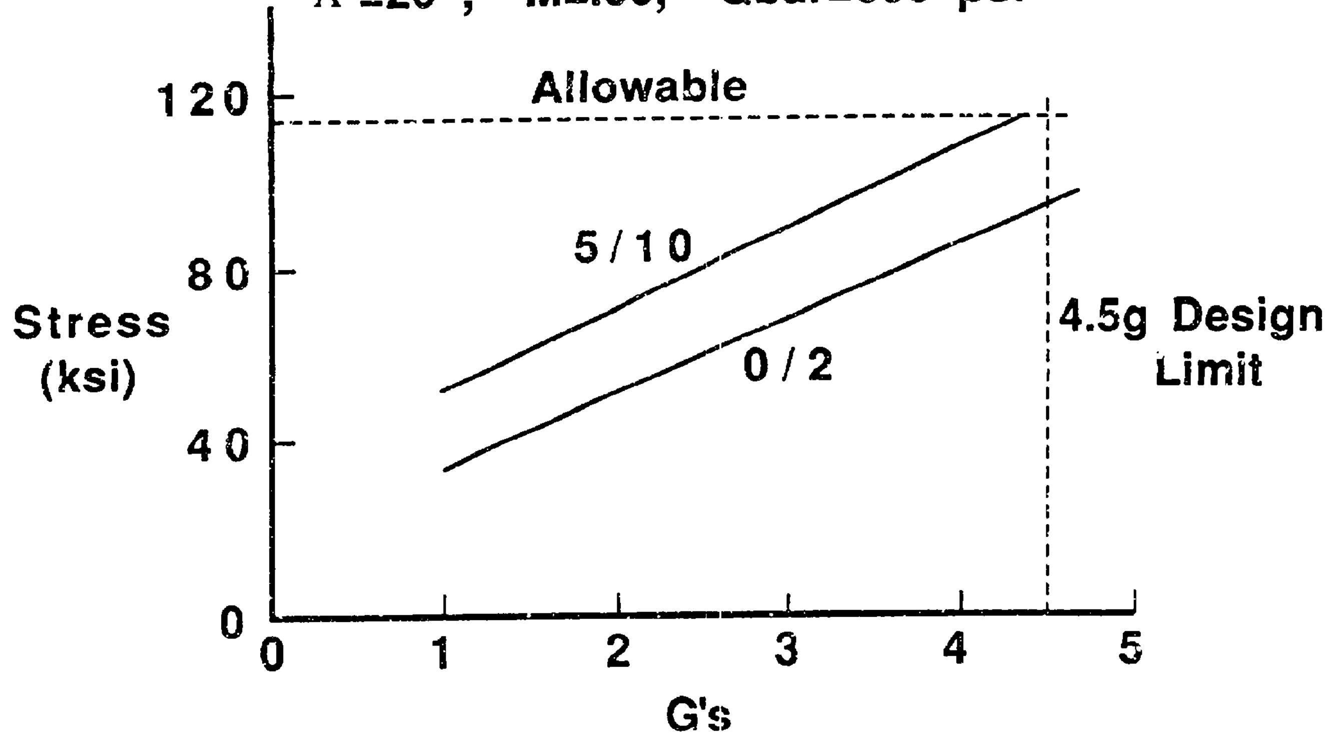
# CRITICAL LOADS PARAMETERS




C3026.010

# Wing Pivot Plate Stress

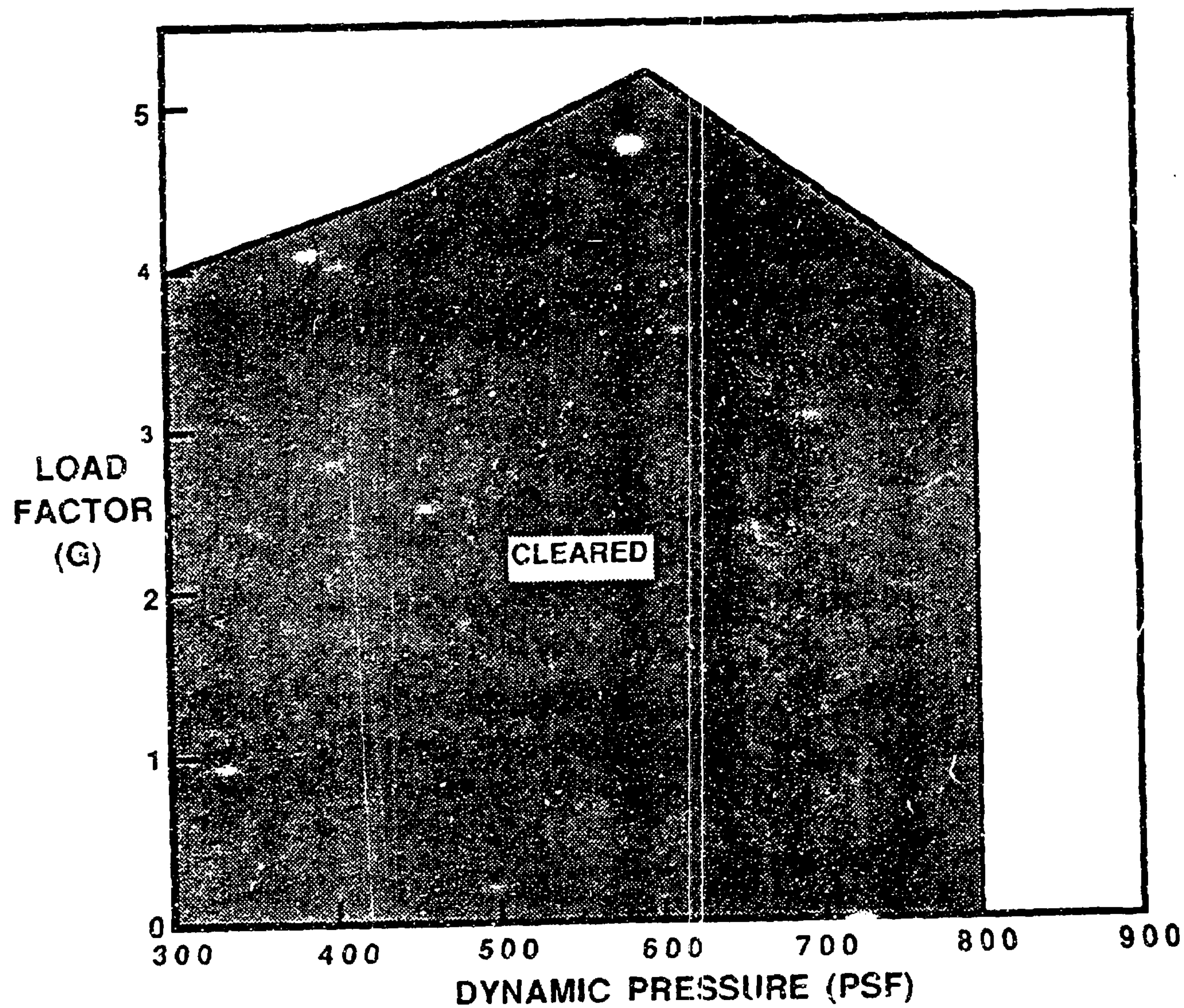
$\Lambda = 26^\circ$, M=.80, Qbar=600 psf



11-2-87
ST

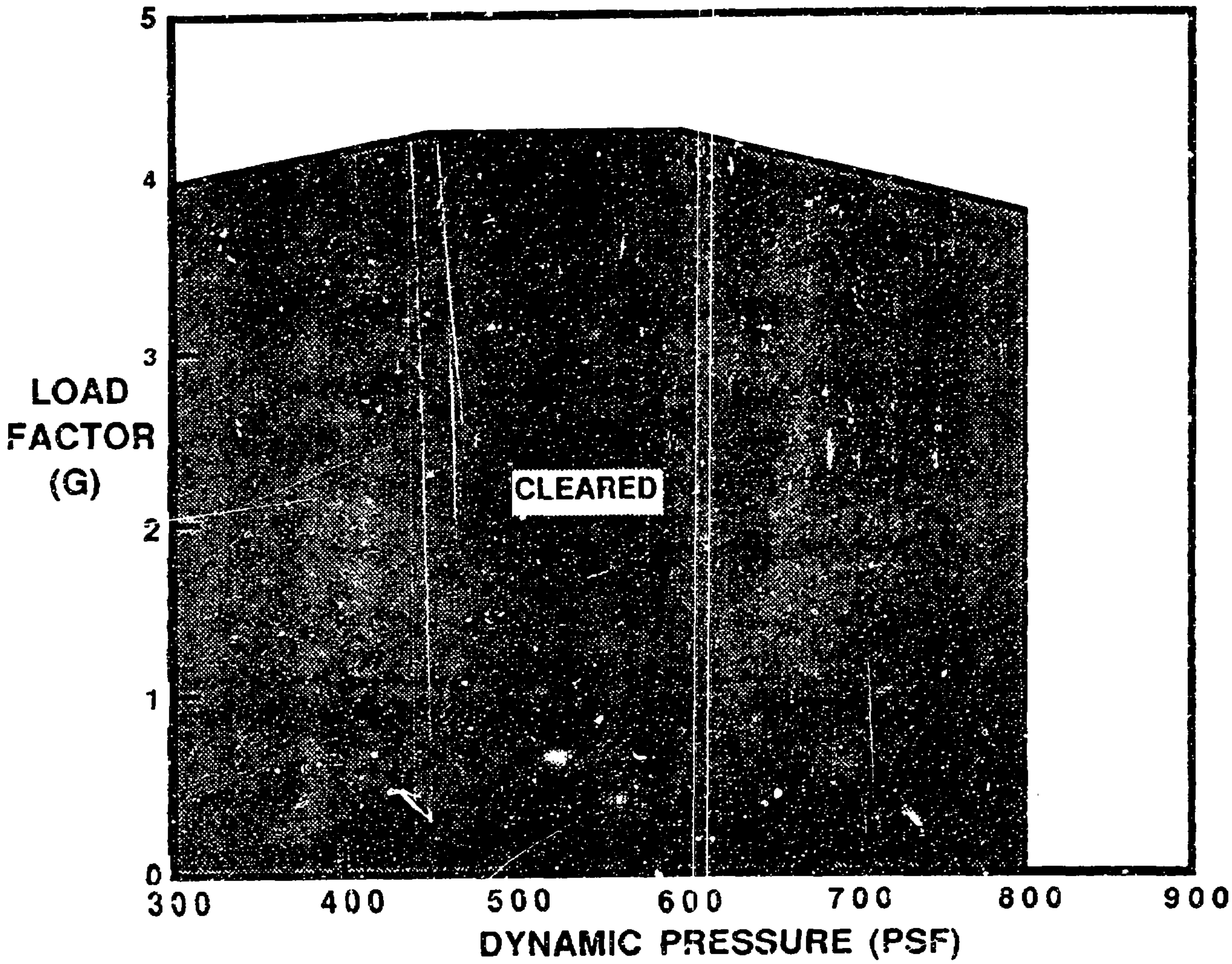
# AFTI/F-111 FLIGHT LOADS ENVELOPE

$\Lambda = 26°$  CAMBER = 0/2,10/2



# AFTI/F-111 FLIGHT LOADS ENVELOPE

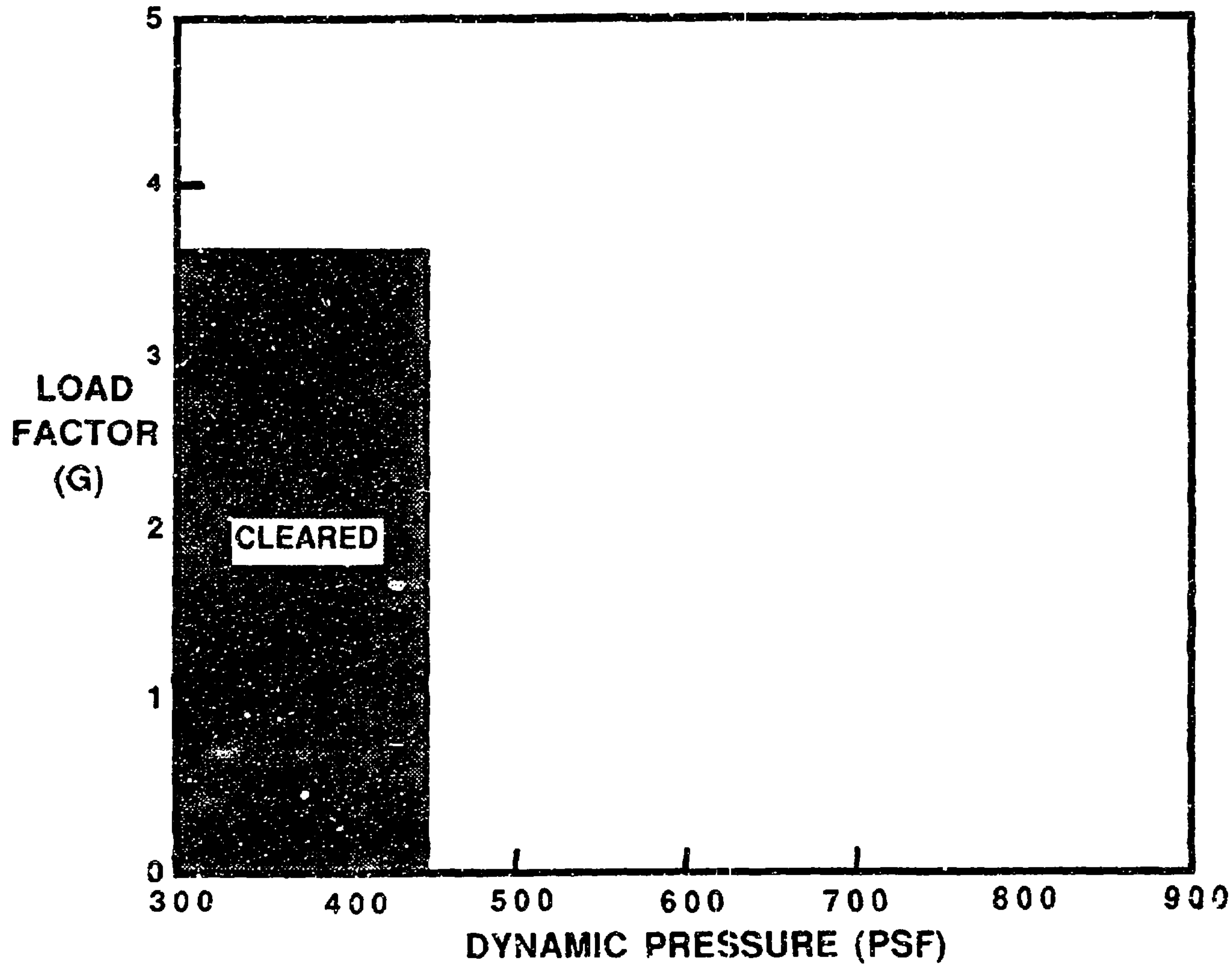
$\Lambda = 26^{\circ}$ CAMBER = 5/10 DEG



10-15-87
ST

# AFTI/F-111 FLIGHT LOADS ENVELOPE

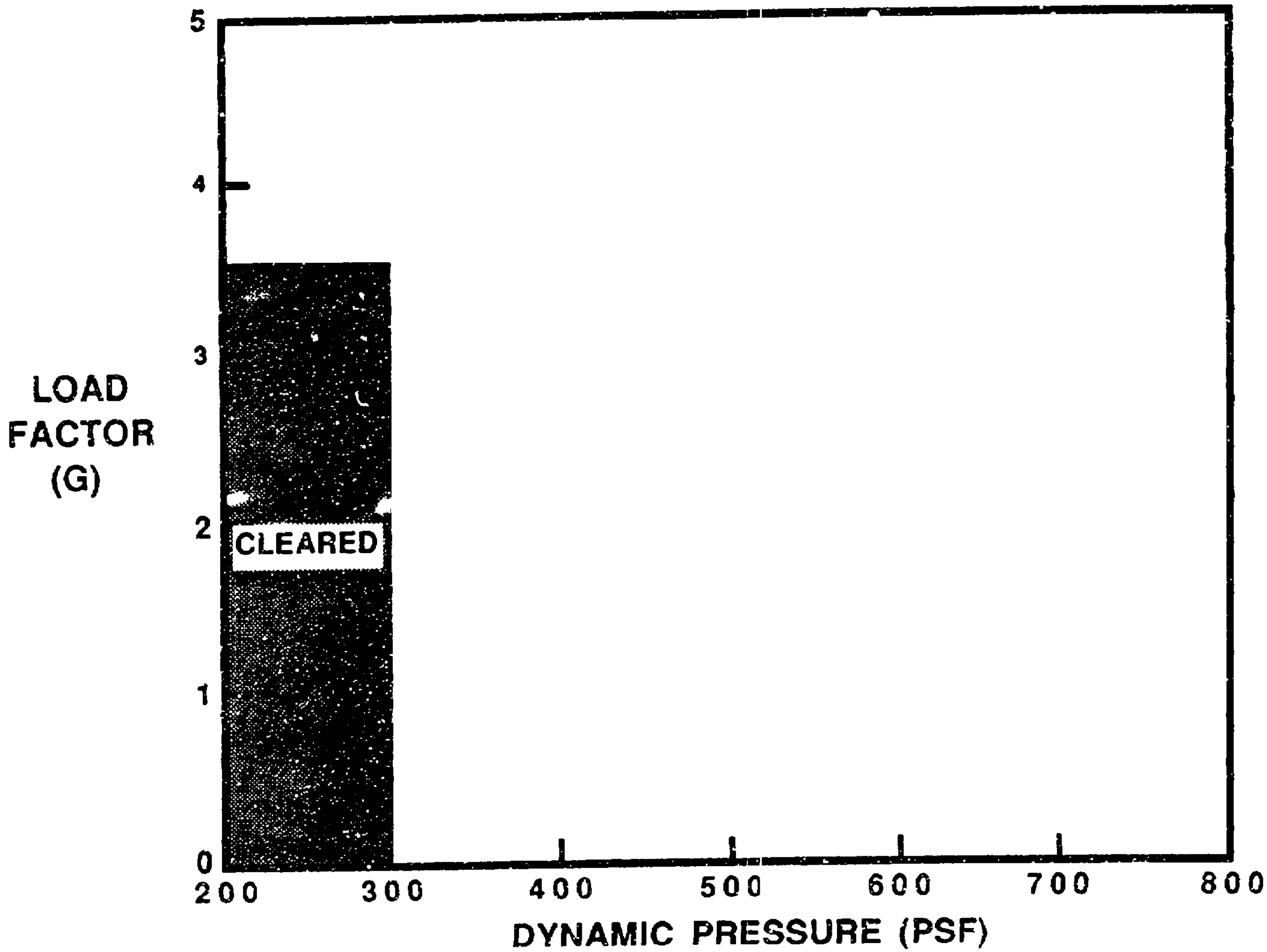
$\Lambda = 26°$ CAMBER = 5/15



ST
6-8-88

# AFTI/F-111 FLIGHT LOADS ENVELOPE

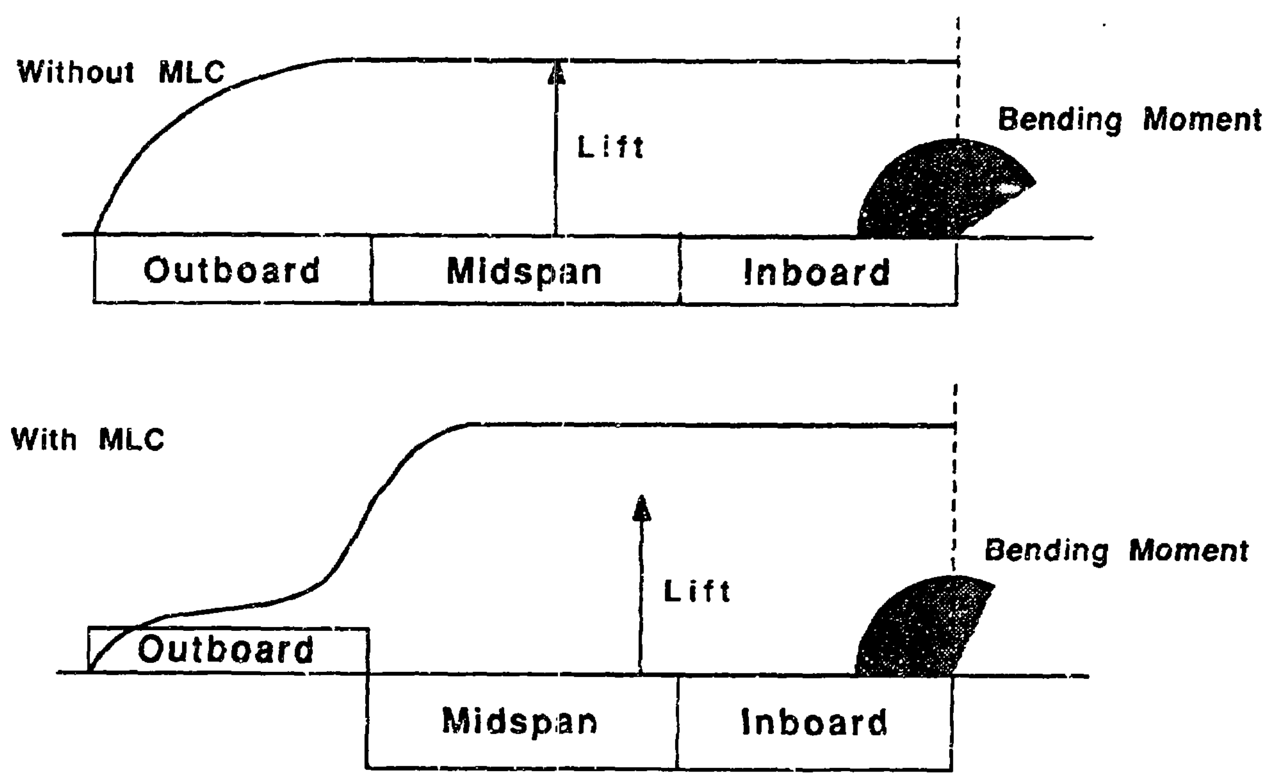
$\Lambda = 26^{\circ}$ CAMBER = 10/18



AFTI/F-111

ST
7-1-88

# MANEUVER LOAD CONTROL (MLC)



# MLC TEST APPROACH

Fly MLC configurations using manually positioned flaps to:

- Quantify bending moment reduction
- Determine trim load increase
- Determine effect of dynamic pressure
- Determine effect of Mach number
- Determine effect of flap position

# SIMULATED MLC VARIABLES INVESTIGATED

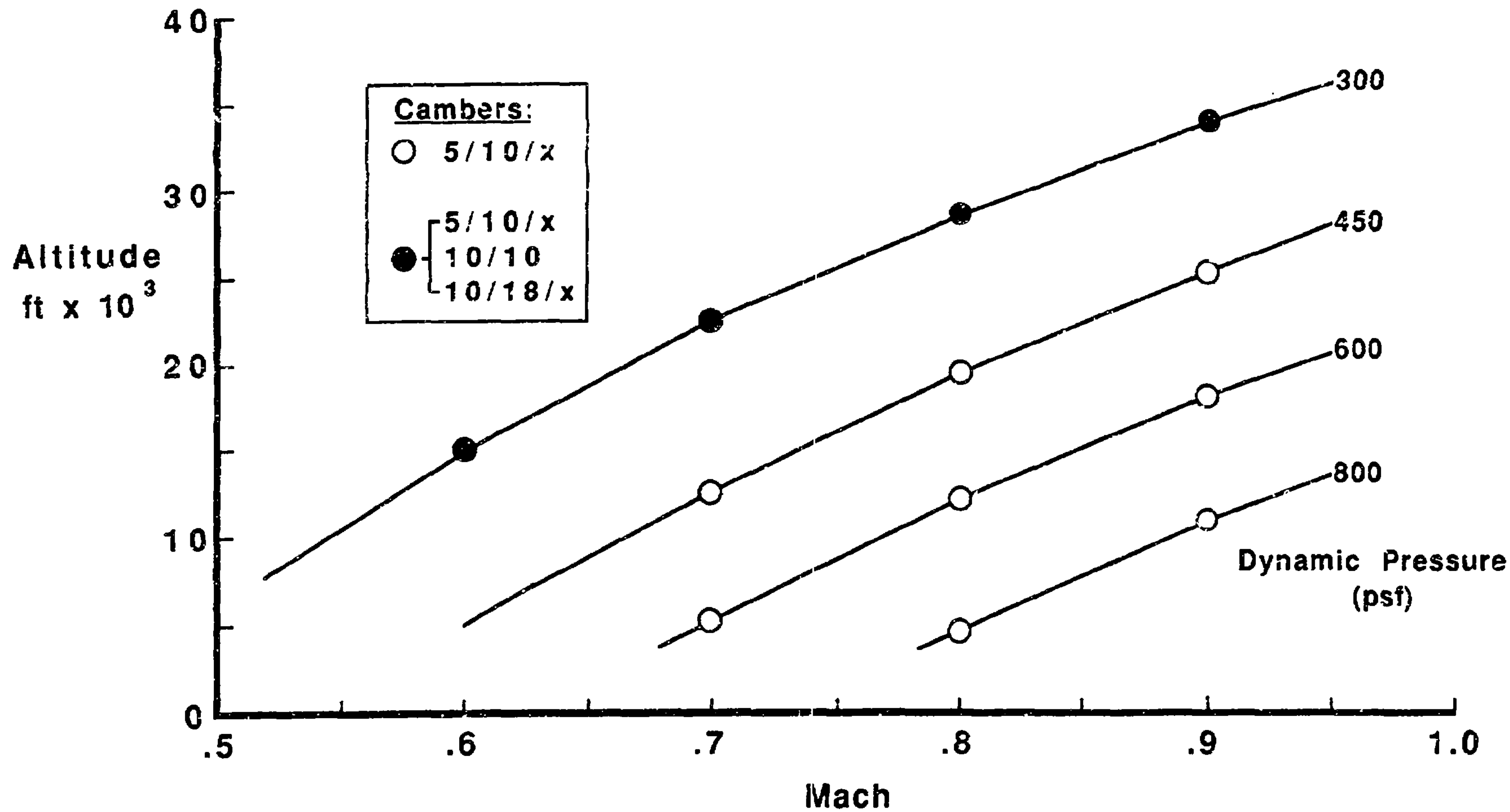
<u>Independent Variables</u>

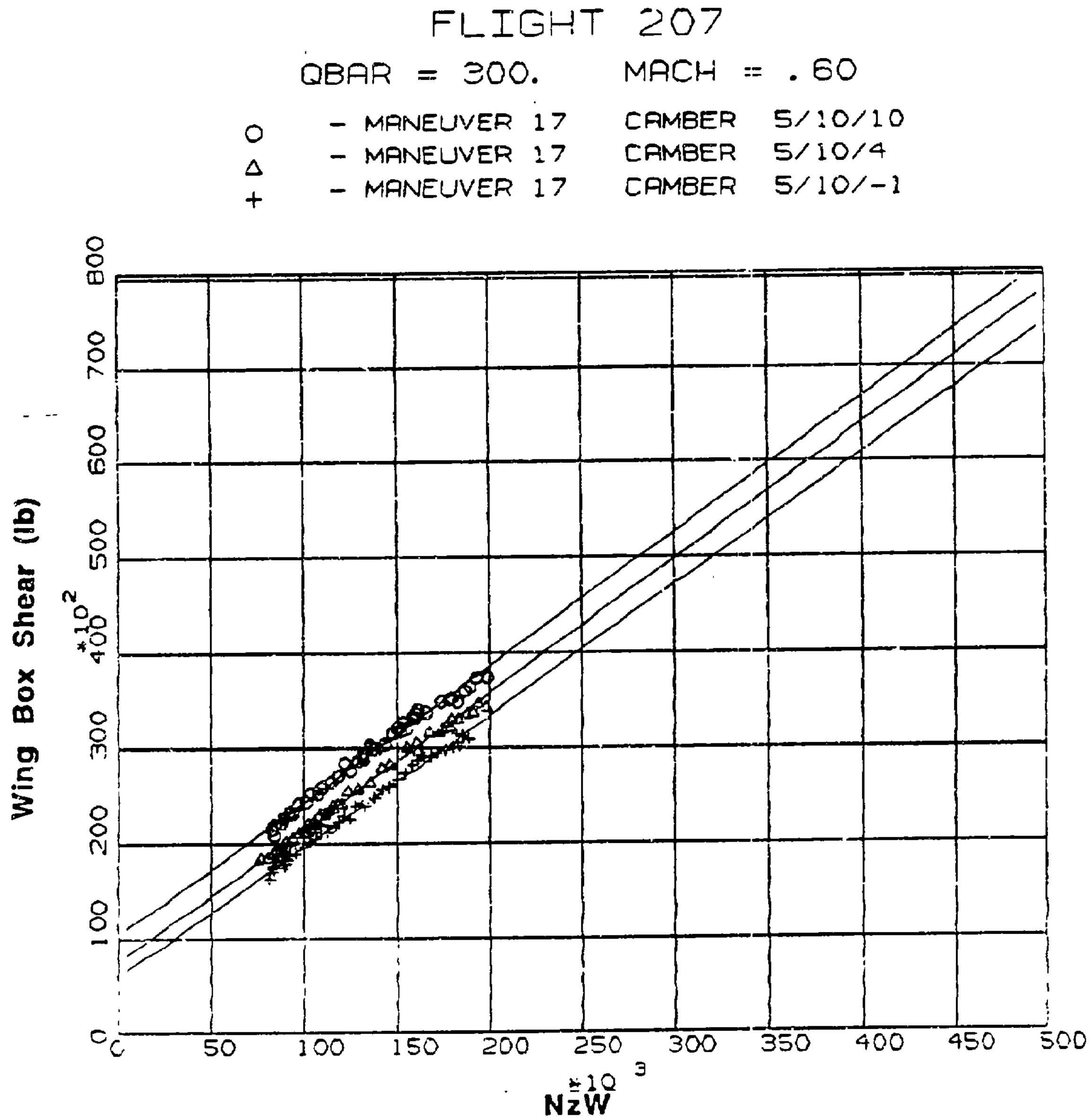
- Mach Number
- Dynamic Pressure
- Flap Position
- Gross Weight

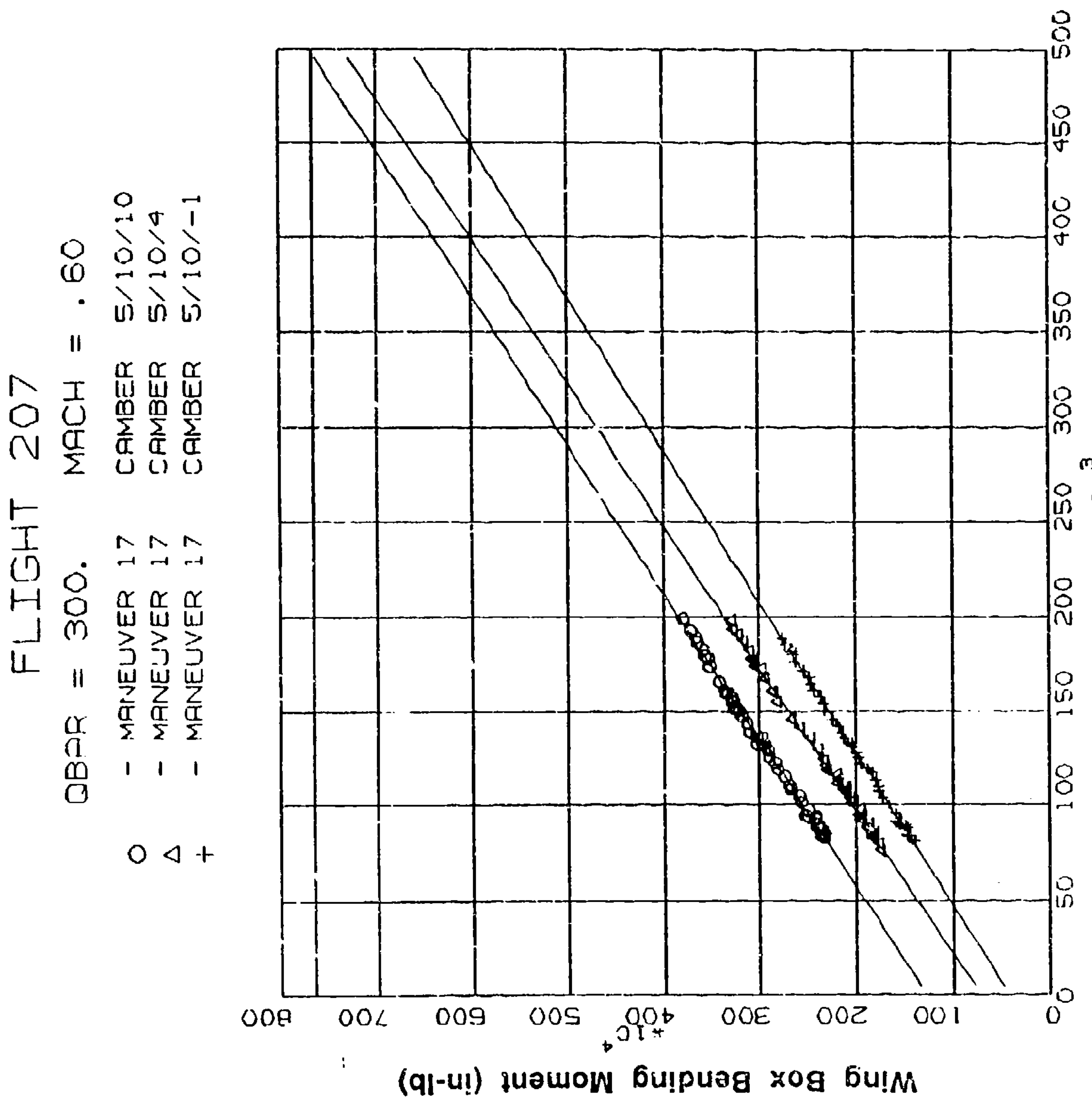
<u>Dependent Variables</u>

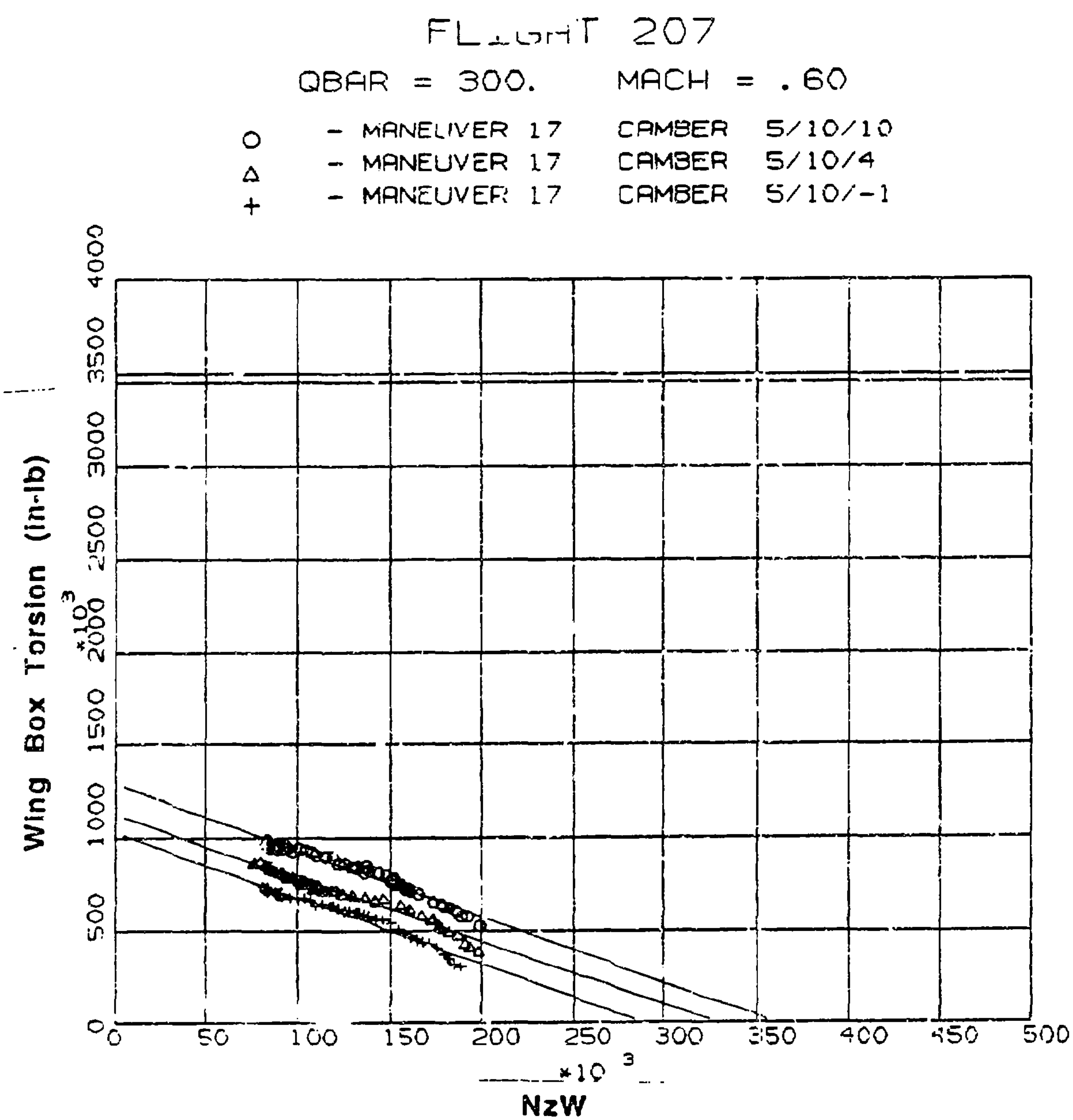
- Wing Bending Moments
- Horizontal Tail Trim Loads
- Load Factor
- Angle of Attack

# FLIGHT LOADS RESEARCH TEST POINTS




FLIGHT 207
QBAR = 300. MACH = .60
○ – MANEUVER 17 CAMBER 5/10/10
△ – MANEUVER 17 CAMBER 5/10/4
+ – MANEUVER 17 CAMBER 5/10/-1
Wing Box Shear (lb)
*10^2
0
100
200
300
400
500
600
700
800
0
50
100
150
200
250
300
350
400
450
500
NzW
*10^3

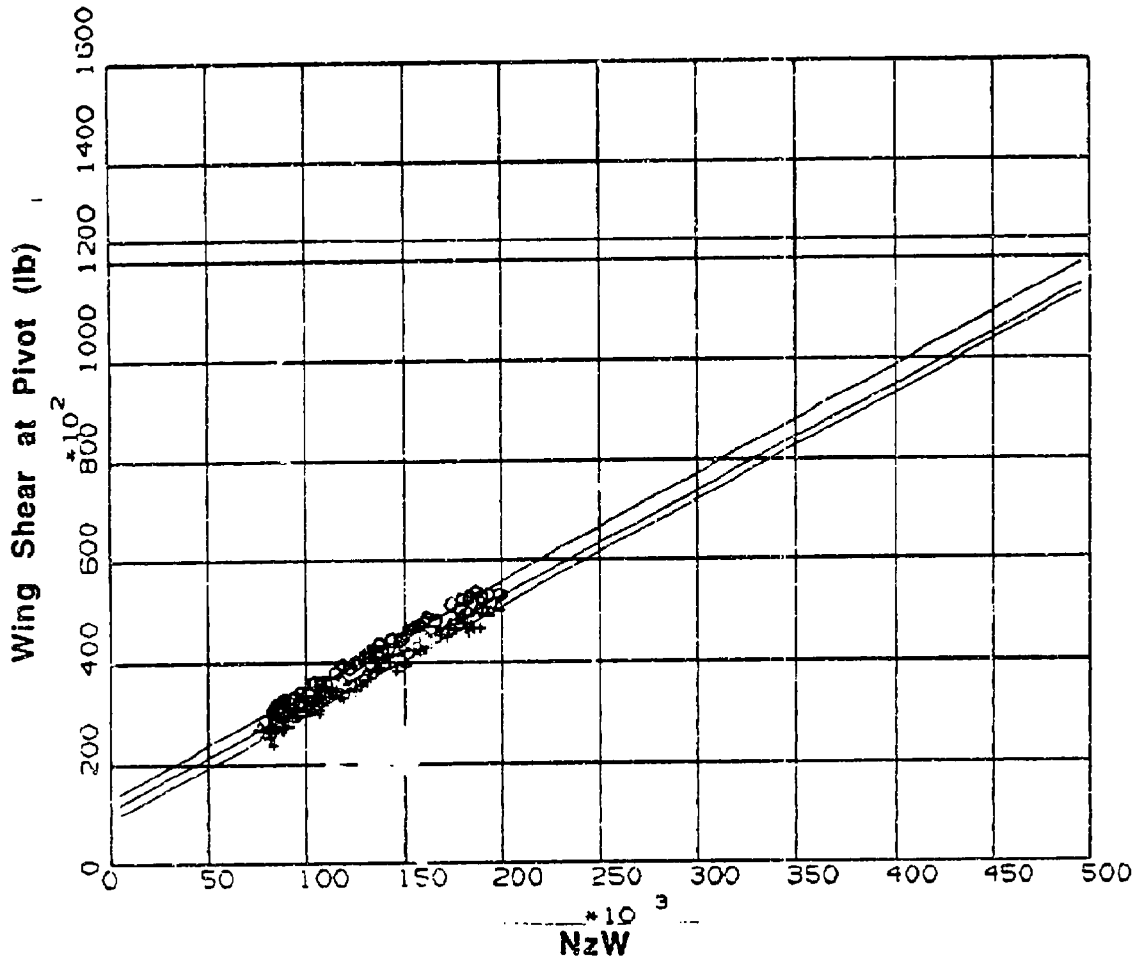

FLIGHT 207
QBAR = 300. MACH = .60
O - MANEUVER 17 CAMBER 5/10/10
Δ - MANEUVER 17 CAMBER 5/10/4
+ - MANEUVER 17 CAMBER 5/10/-1
Wing Box Bending Moment (in-lb)
*10^4
0
100
200
300
400
500
600
700
800
NzW
*10^3
0
50
100
150
200
250
300
350
400
450
500


FLIGHT 207
QBAR = 300.   MACH = .60
○ - MANEUVER 17   CAMBER 5/10/10
△ - MANEUVER 17   CAMBER 5/10/4
+ - MANEUVER 17   CAMBER 5/10/-1
Wing Box Torsion (in-lb)
*10³
0
500
1000
1500
2000
2500
3000
3500
4000
0
50
100
150
200
250
300
350
400
450
500
*10³
NzW

FLIGHT 207

QBAR = 300. MACH = .60

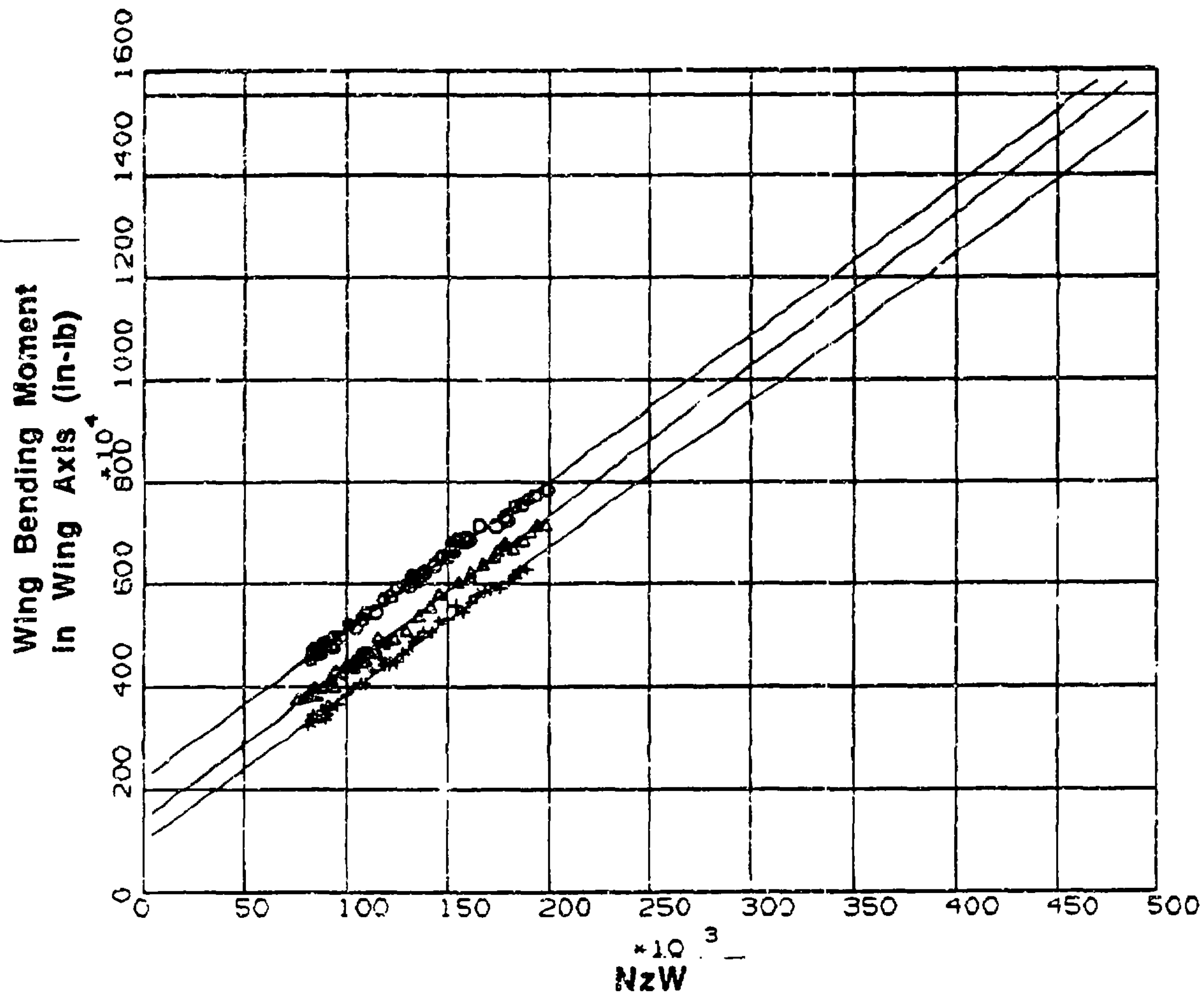
○ - MANEUVER 17 CAMBER 5/10/10
△ - MANEUVER 17 CAMBER 5/10/4
+ - MANEUVER 17 CAMBER 5/10/-1

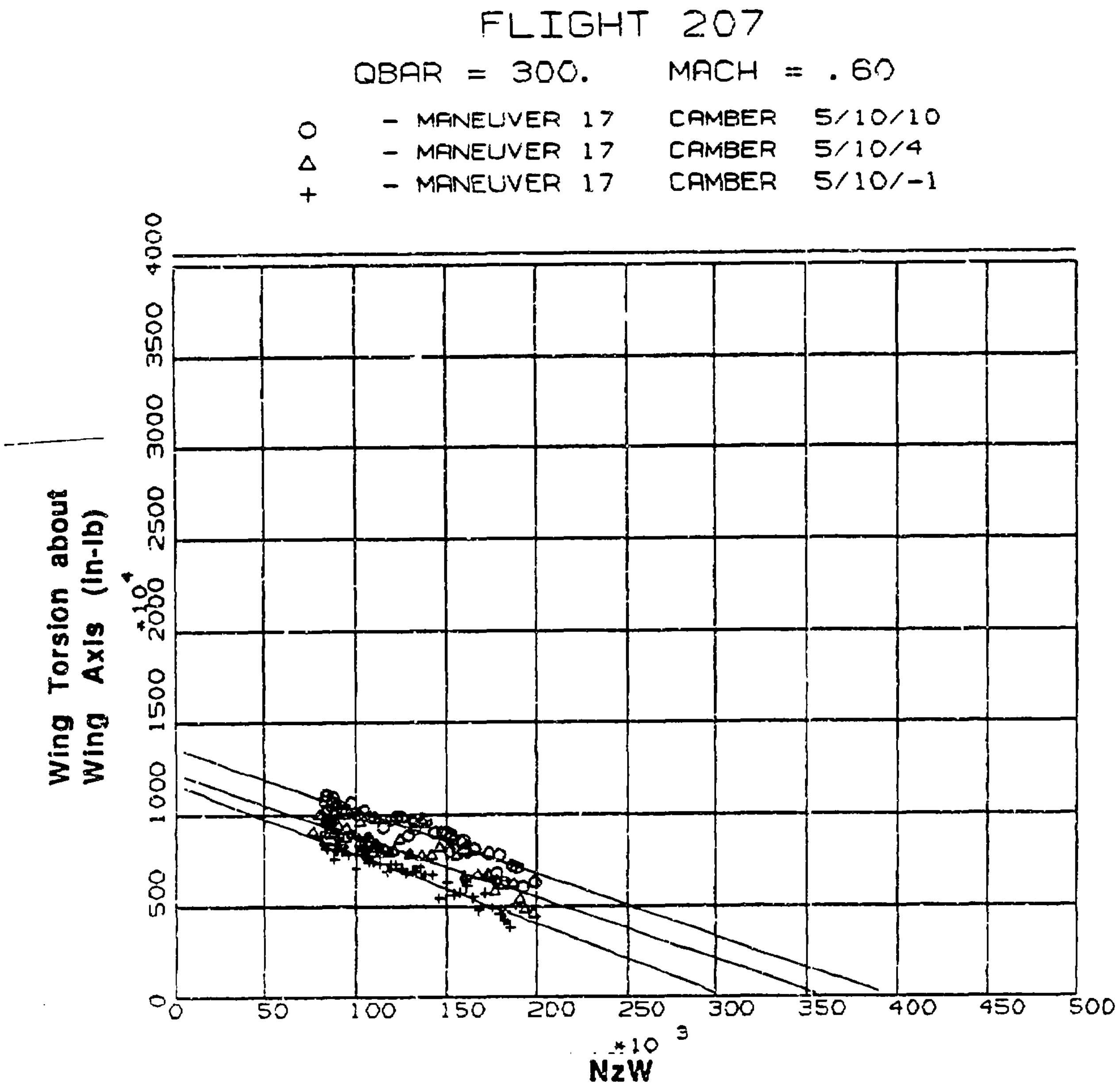


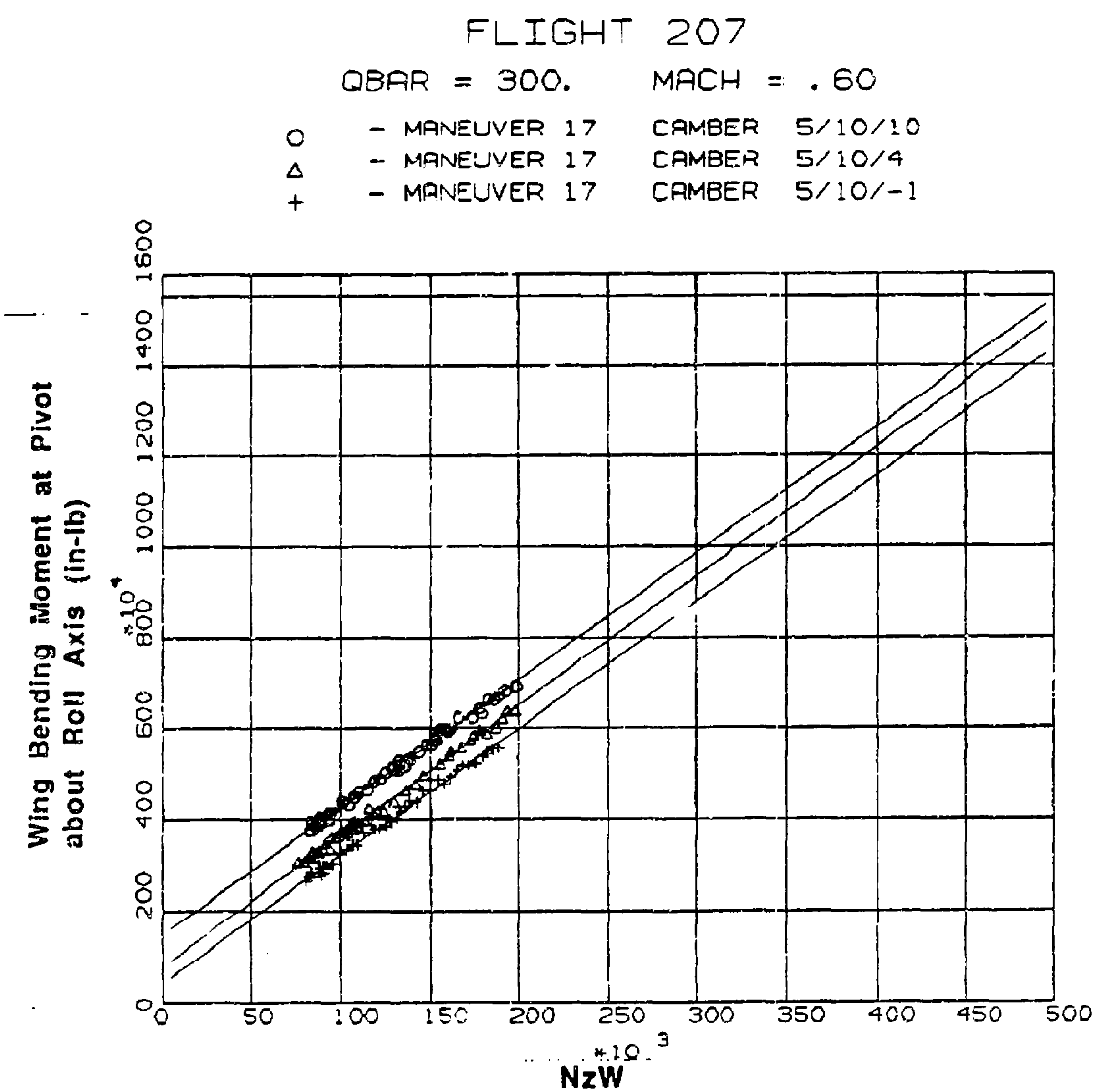
FLIGHT 207

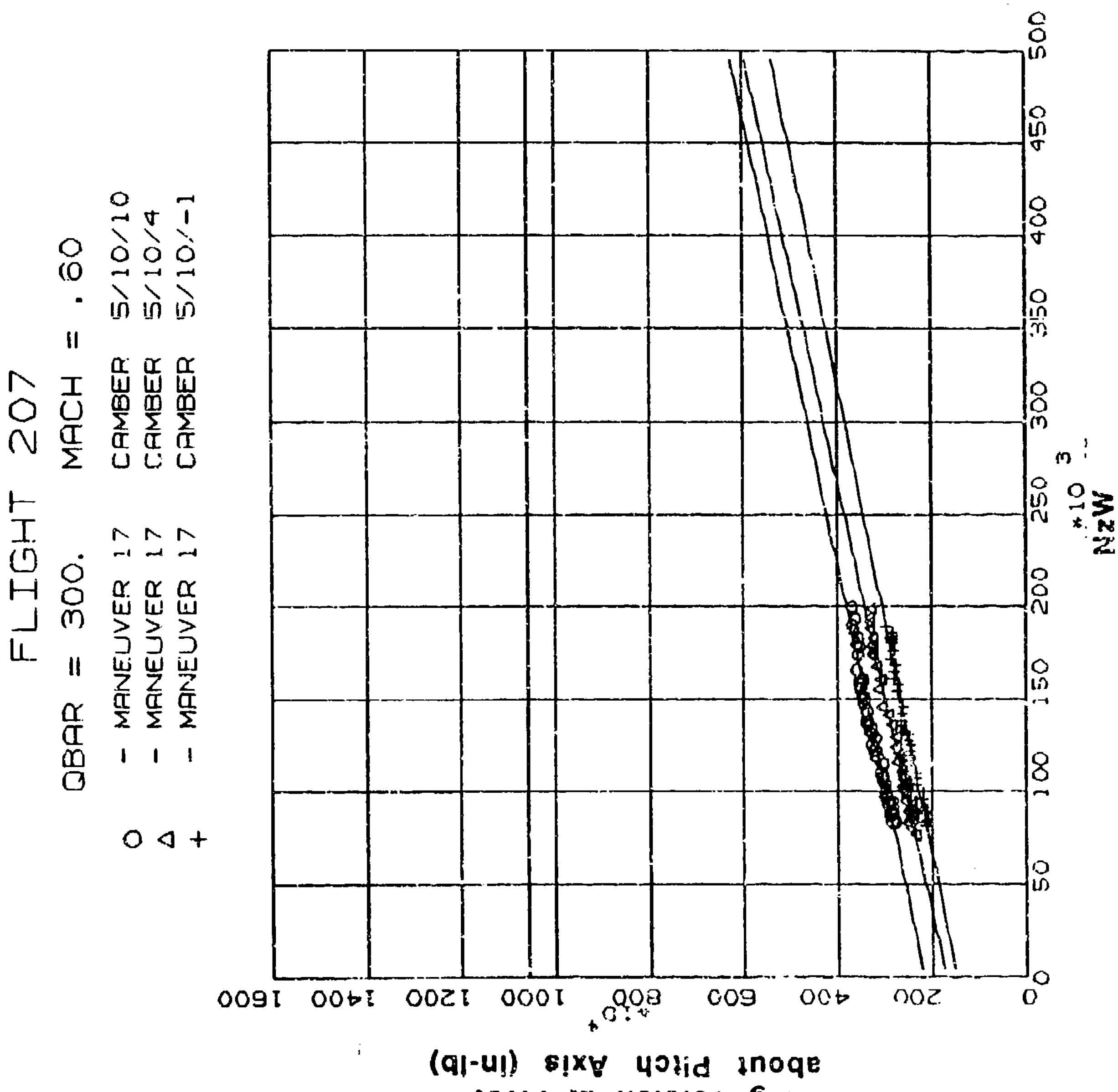
QBAR = 300.    MACH = .60

○ - MANEUVER 17    CAMBER 5/10/10
△ - MANEUVER 17    CAMBER 5/10/4
+ - MANEUVER 17    CAMBER 5/10/-1

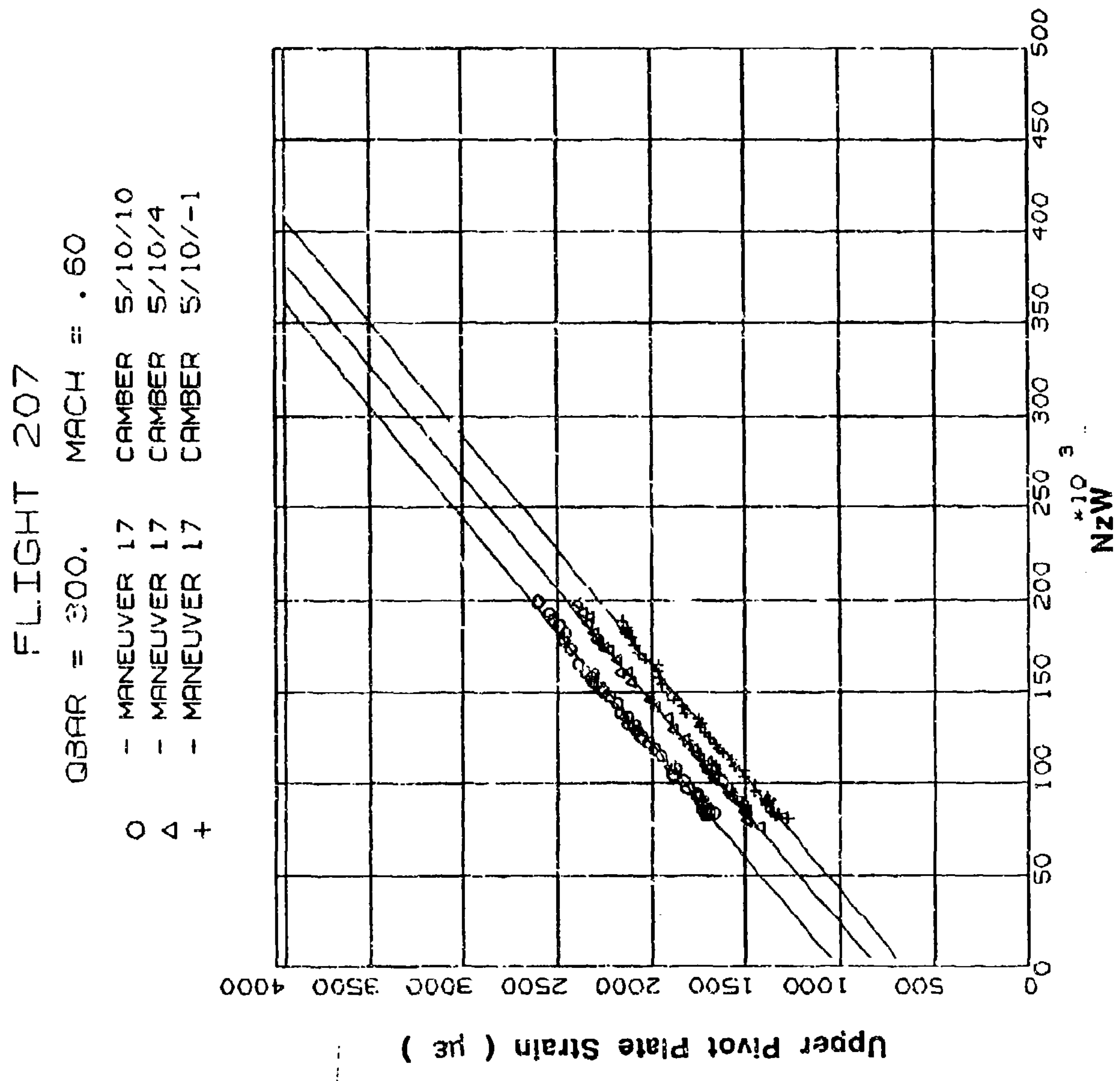


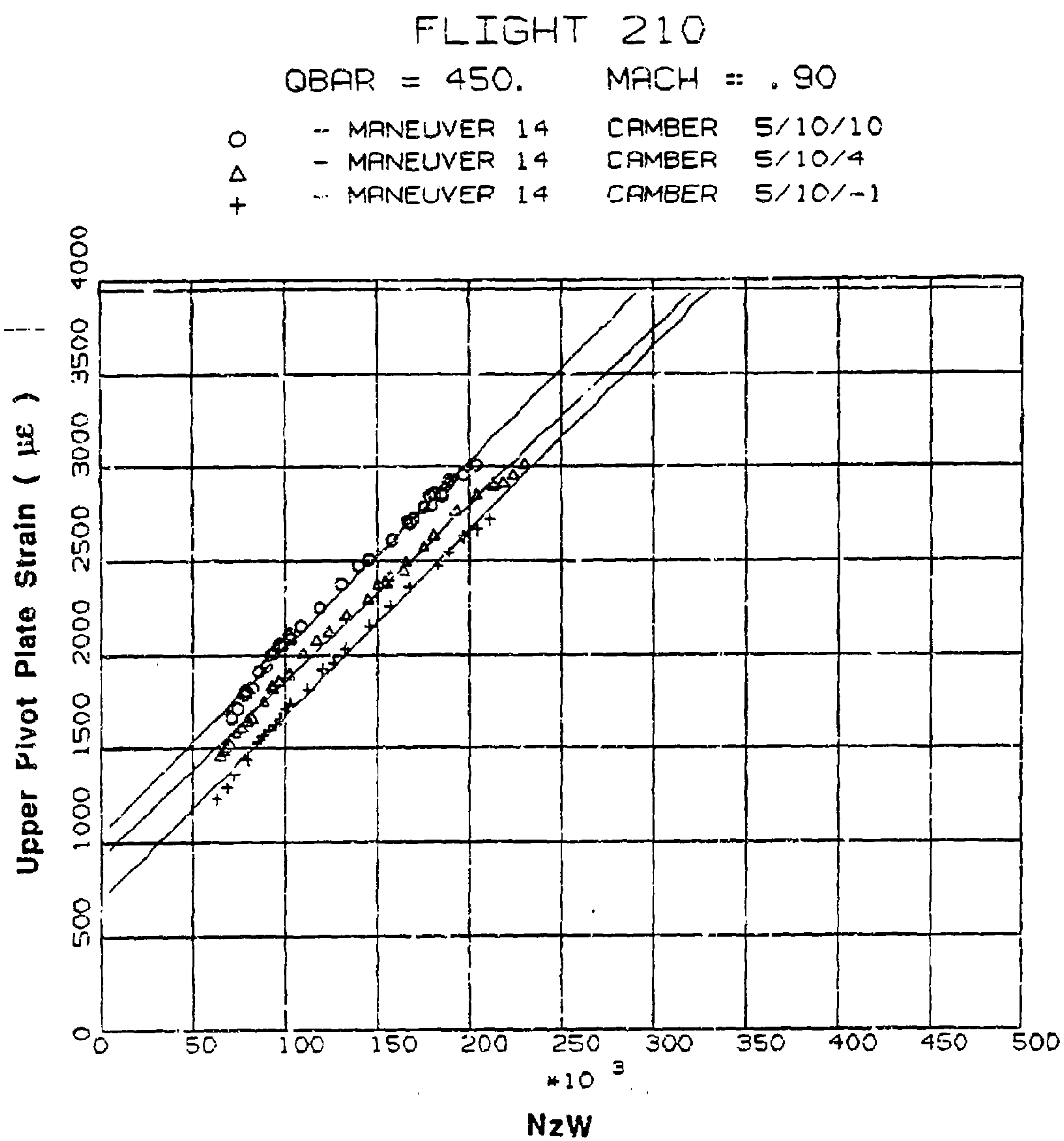

FLIGHT 207
QBAR = 300.   MACH = .60
○ - MANEUVER 17   CAMBER 5/10/10
△ - MANEUVER 17   CAMBER 5/10/4
+ - MANEUVER 17   CAMBER 5/10/-1
Wing Torsion about Wing Axis (In-lb)
*10^4
0
500
1000
1500
2000
2500
3000
3500
4000
0
50
100
150
200
250
300
350
400
450
500
*10^3
NzW

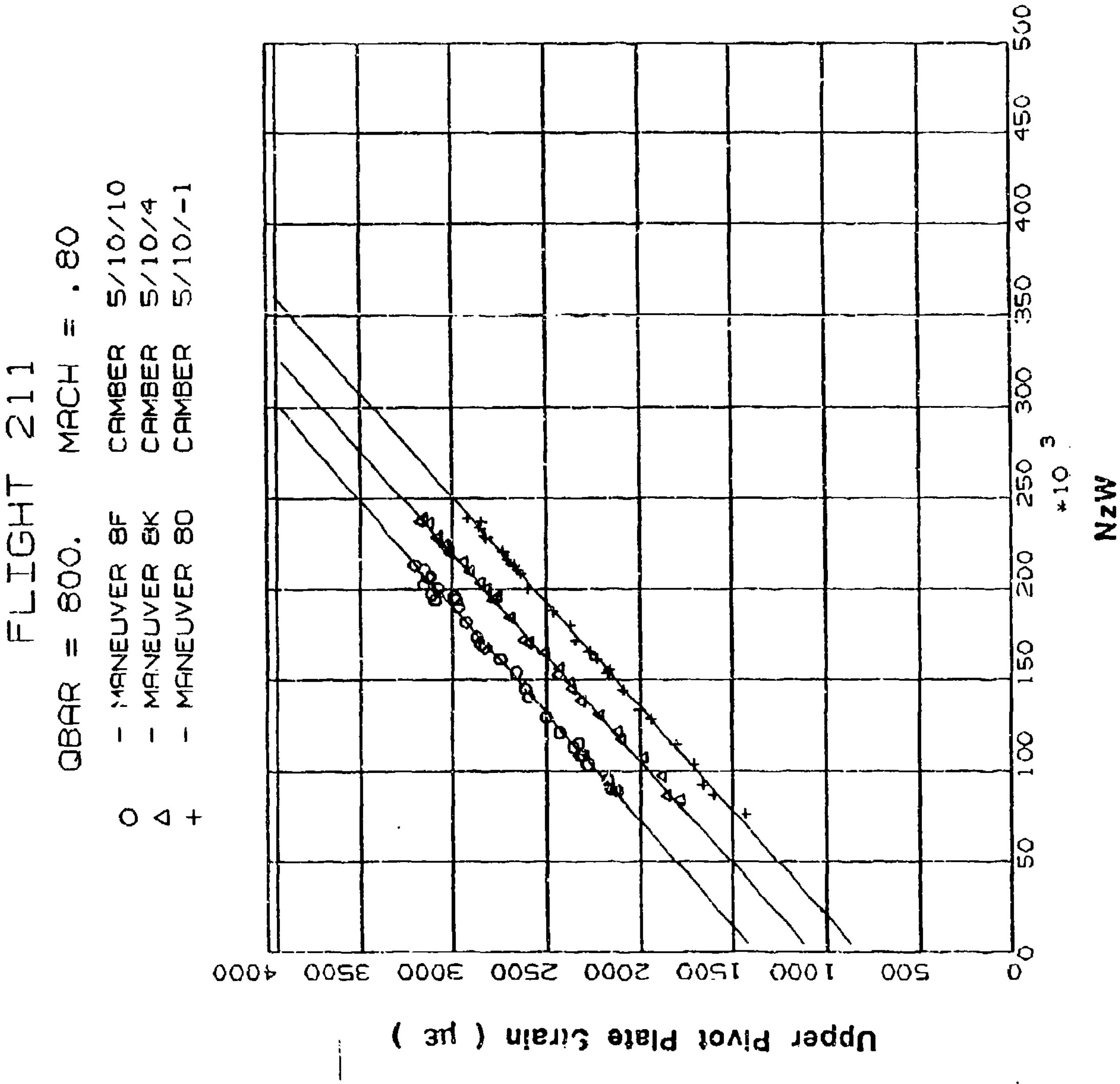

FLIGHT 207
QBAR = 300.   MACH = .60
○ - MANEUVER 17 CAMBER 5/10/10
△ - MANEUVER 17 CAMBER 5/10/4
+ - MANEUVER 17 CAMBER 5/10/-1
Wing Bending Moment at Pivot about Roll Axis (in-lb)
*10^4
0
200
400
600
800
1000
1200
1400
1600
0
50
100
150
200
250
300
350
400
450
500
*10^3
NzW



FLIGHT 207
QBAR = 300. MACH = .60
○ - MANEUVER 17 CAMBER 5/10/10
△ - MANEUVER 17 CAMBER 5/10/4
+ - MANEUVER 17 CAMBER 5/10/-1
0 50 100 150 200 250 300 350 400 450 500
NzW *10 3
0 200 400 600 800 1000 1200 1400 1600
*10 4
Wing Torsion at Pivot about Pitch Axis (in-lb)


FLIGHT 207
QBAR = 300.   MACH = .60
O - MANEUVER 17   CAMBER 5/10/10
Δ - MANEUVER 17   CAMBER 5/10/4
+ - MANEUVER 17   CAMBER 5/10/-1
0 500 1000 1500 2000 2500 3000 3500 4000
Upper Pivot Plate Strain ( με )
0 50 100 150 200 250 300 350 400 450 500
NzW *10 3

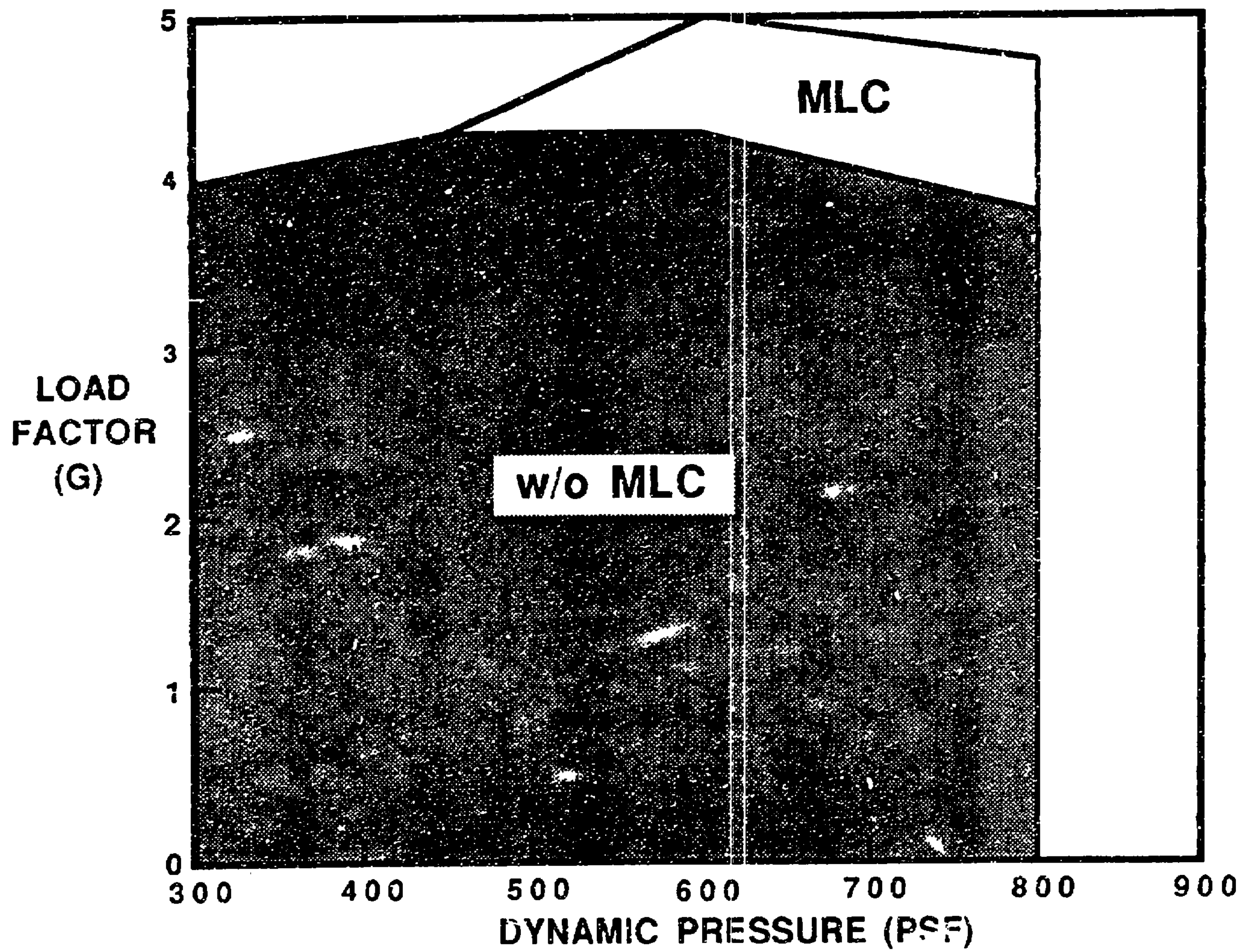

FLIGHT 210
QBAR = 450.    MACH = .90
○ -- MANEUVER 14    CAMBER 5/10/10
△ - MANEUVER 14    CAMBER 5/10/4
+ -- MANEUVER 14    CAMBER 5/10/-1
Upper Pivot Plate Strain ( µε )
0
500
1000
1500
2000
2500
3000
3500
4000
0
50
100
150
200
250
300
350
400
450
500
*10 3
NzW



FLIGHT 211
QBAR = 800. MACH = .80
○ - MANEUVER 8F CAMBER 5/10/10
△ - MANEUVER 8K CAMBER 5/10/4
+ - MANEUVER 80 CAMBER 5/10/-1
Upper Pivot Plate Strain ( με )
0
500
1000
1500
2000
2500
3000
3500
4000
NzW
*10 3
50
100
150
200
250
300
350
400
450
500

# POTENTIAL LOADS ENVELOPE W/MLC

$\Lambda = 26°$ CAMBER = 5/10 DEG

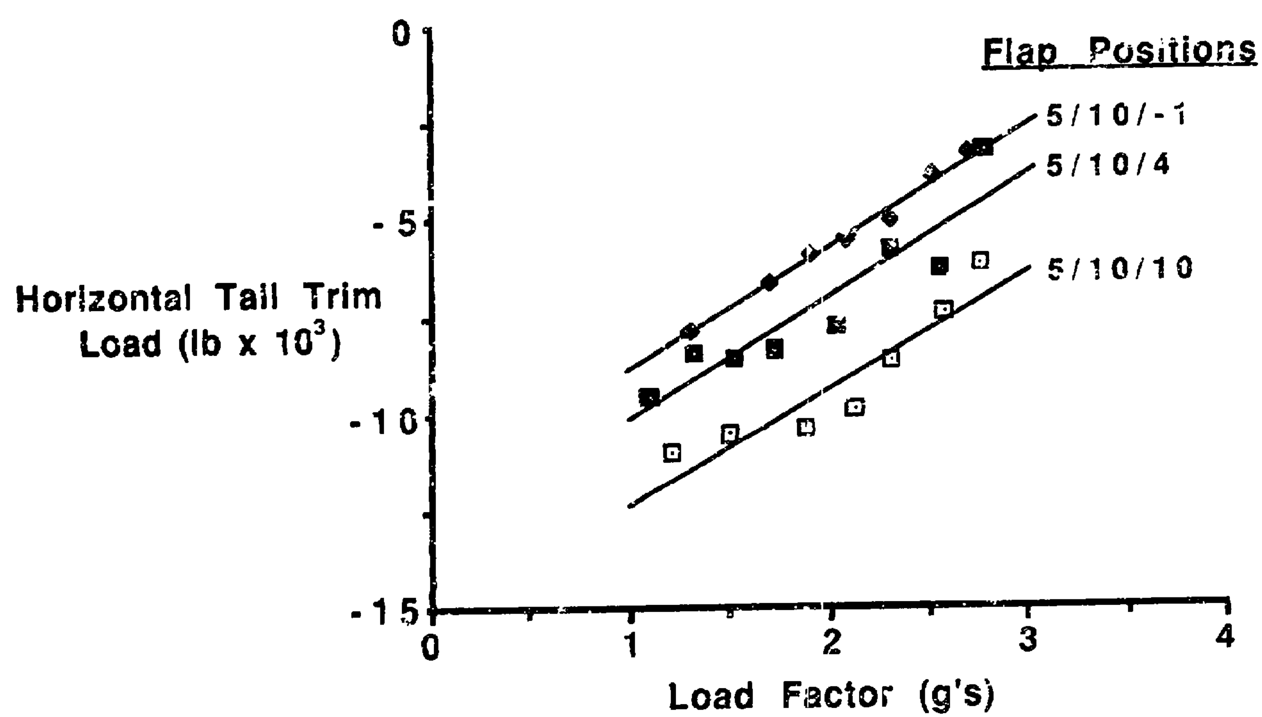


AFTI/F-111

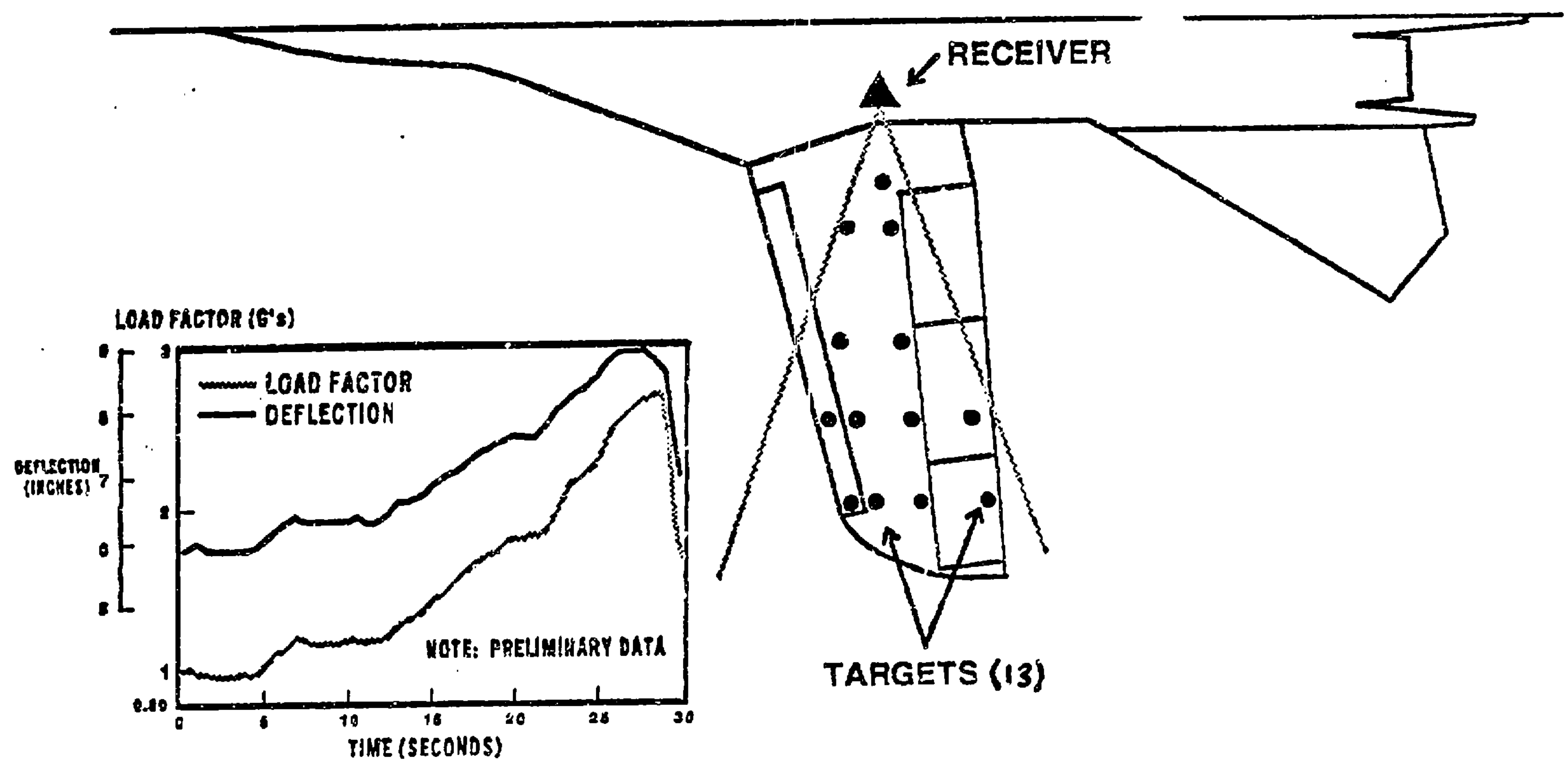
ST
7-13-88

# MLC HORIZONTAL TAIL TRIM LOADS

Mach = .60 Qbar = 300 psf



# AFTI/F-111 FLIGHT DEFLECTION MEASUREMENT SYSTEM




C3028.016

AFTI/F-111

ST
7-12-88

# MLC PRELIMINARY CONCLUSIONS

- 10 - 20% Reduction in Wing Root Bending Moment
- 5-15% Reductions in Other Wing Load Parameters
- Potential for Significant Expansion of Basic Loads Envelope

NASA
AD88-850

# Measured and Predicted Pressure Distributions on the AFTI/F-111 Mission Adaptive Wing

**Lannie D. Webb**
NASA Ames Dryden Flight Research Facility
Edwards, California

**William E. McCain and Lucinda A. Rose**
PRC Systems Services
Edwards, California

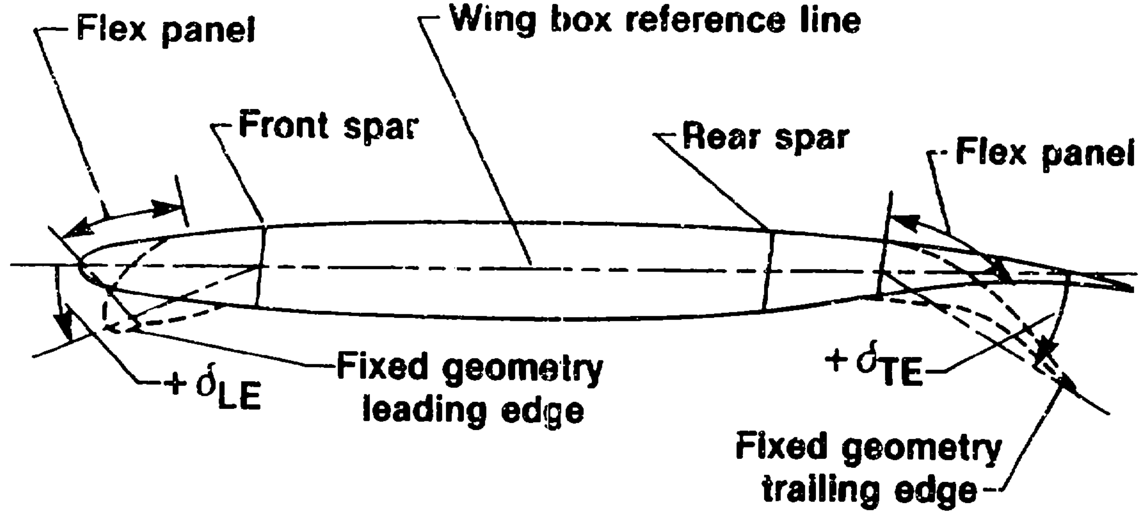
# Objectives

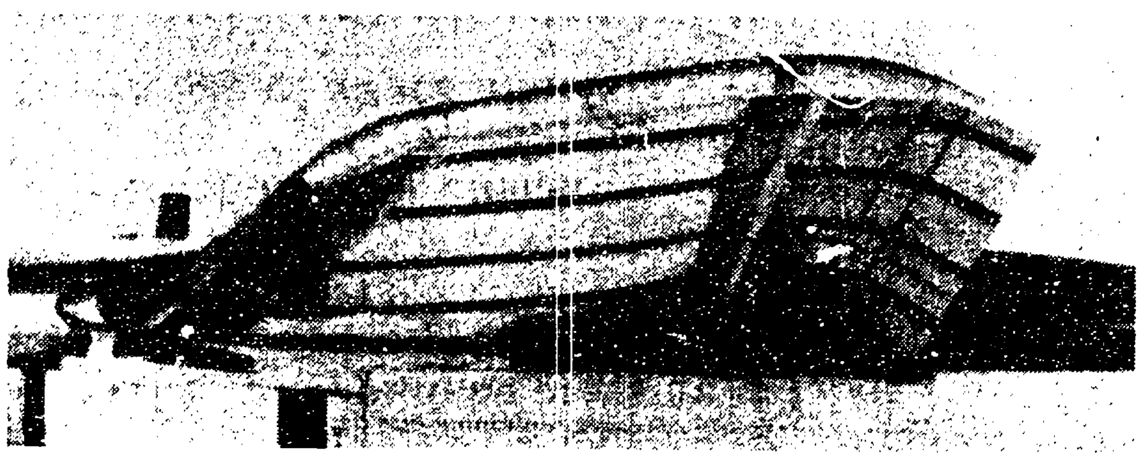
NASA
AD88-861

- Establish wing surface pressure database
  - Span effects
  - Mach number effects
  - Angle-of-attack effects
  - Camber effects
- Compare flight and wind-tunnel data
- Compare MAW and TACT data for design changes
- Compare flight and predicted data

# Smooth Variable Camber of the MAW

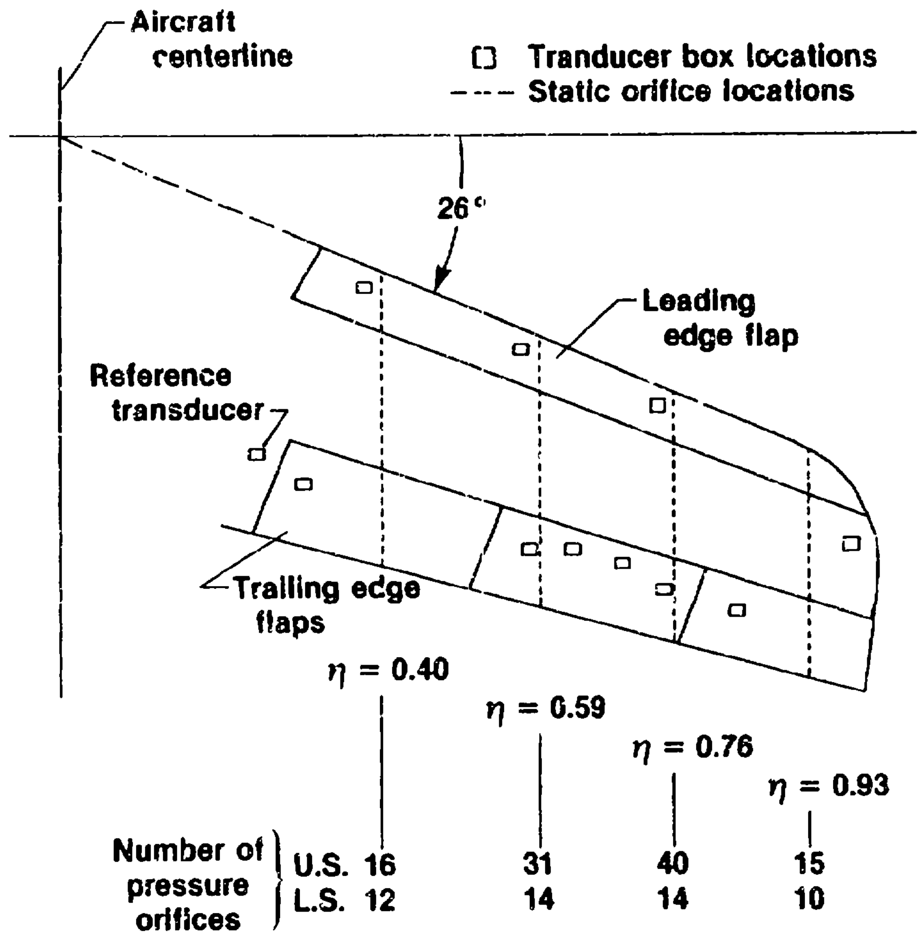
NASA
AD86-874



# Static Pressure Instrumentation

AD88-875



# Flight Data Acquisition Techniques and Data Selection

- Trim for one minute
- Slow wind-up turns to short stabilized conditions (sustained angle-of-attack/Mach number turns) or push-over pull-ups for low angles of attack
- Wind-tunnel conditions matched

  $4° \leq \alpha \leq 12°$

  $0.6 \leq M_\infty \leq 0.90$

  $\delta_{LE/TE} = 0/2$ --- $20/18$

---

- Limits for selection of data

  $M_\infty = M_{\infty_{AIM}} \pm 0.01$

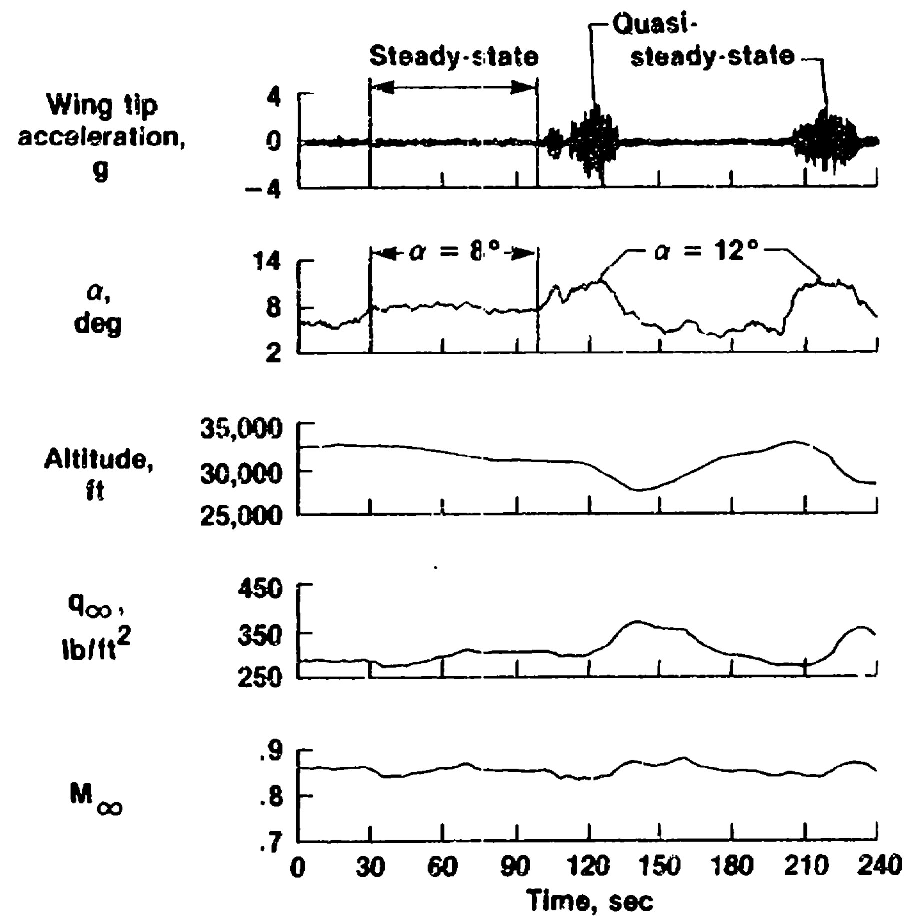
  $\alpha = \alpha_{AIM} \pm 0.25°$

  $\beta = 0° \pm 0.25°$

  H = Quasi-Steady-State

# Time History for a Typical Maneuver

NASA
AD88-876a



# Flight Data Base Collected

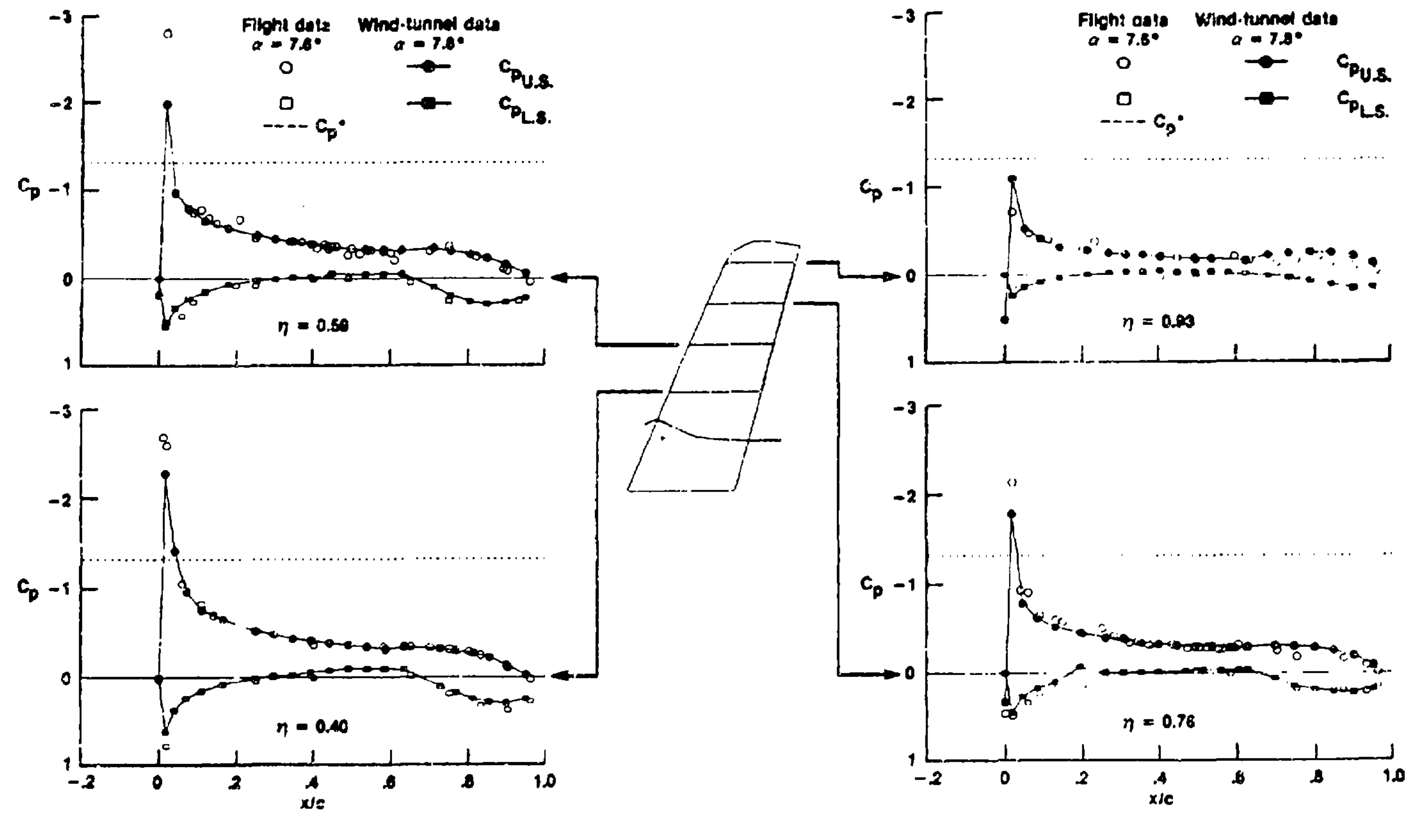
- $M_\infty$ = 0.6, $\underline{0.8}$, $\underline{0.85}$*, and $\underline{0.90}$
- $\alpha$ = 4°, $\underline{8}$°, $\underline{10}$°, and $\underline{12}$°
- $\delta_{LE/TE}$ = $\underline{0/2}$*, 5/2, 5/6, $\underline{5/10}$, $\underline{10/2}$, 0/10, 10/10
- $q_\infty$ = 300/600 lb/ft$^2$
- $R_n$ = 2.3 x 10$^6$/ft ( 26 x 10$^6$ based on mean aerodynamic chord )
- Miscellaneous data---from other disciplines ( loads, buffet, automatic modes, etc. )

---

- * Wing cruise design conditions ( 0.45 $C_L$ )
- Conditions underlined were tested at $q_\infty$ = 600 lb/ft$^2$ in addition to $q_\infty$ = 300 lb/ft$^2$ for all the points

# Steady Chordwise Pressure Distributions
## $M_\infty = 0.60$ and $\delta_{LE/TE} = 0/2$

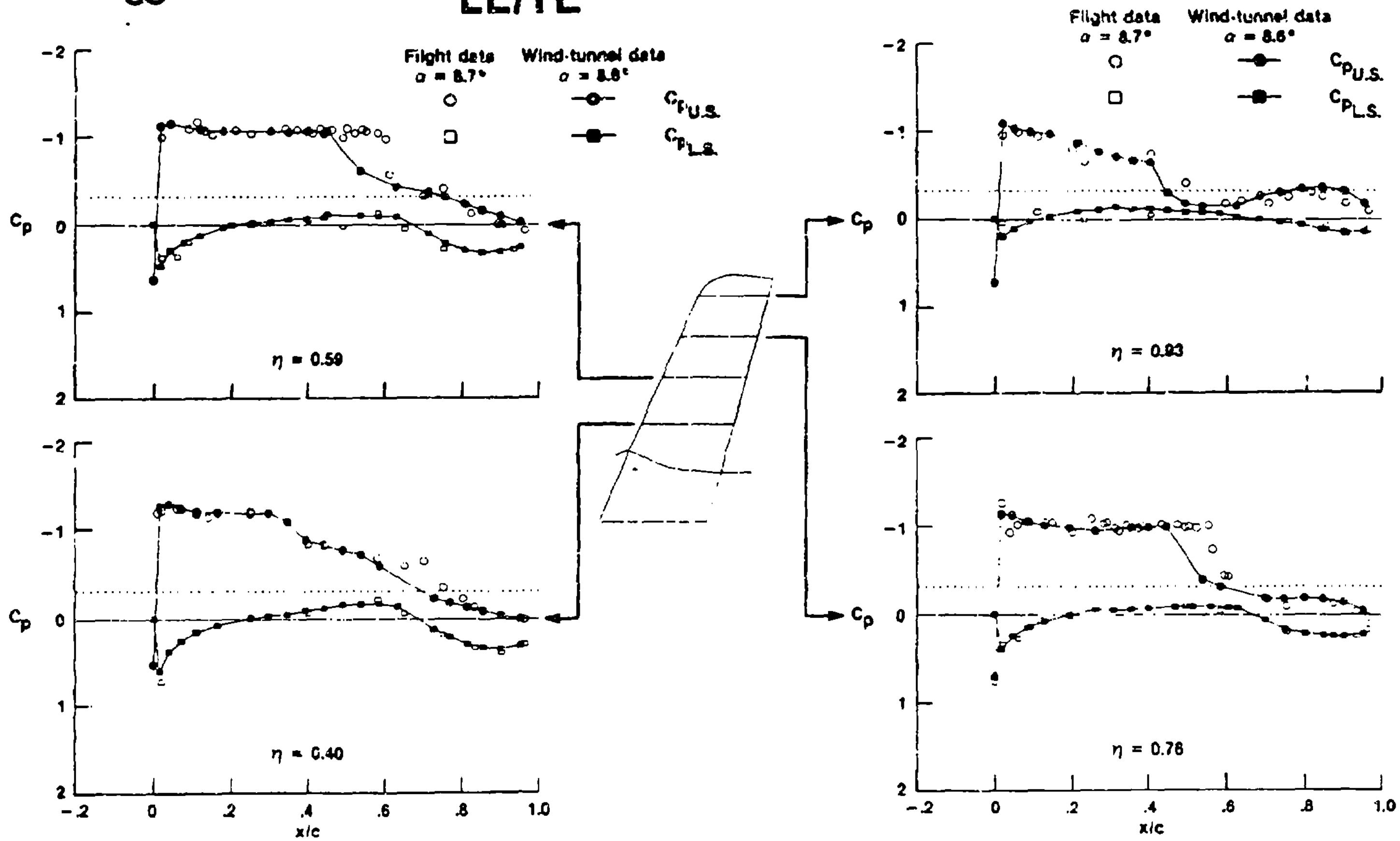
AD88-864



# Steady Chordwise Pressure Distributions

## $M_\infty = 0.85$ and $\delta_{LE/TE} = 0/2$

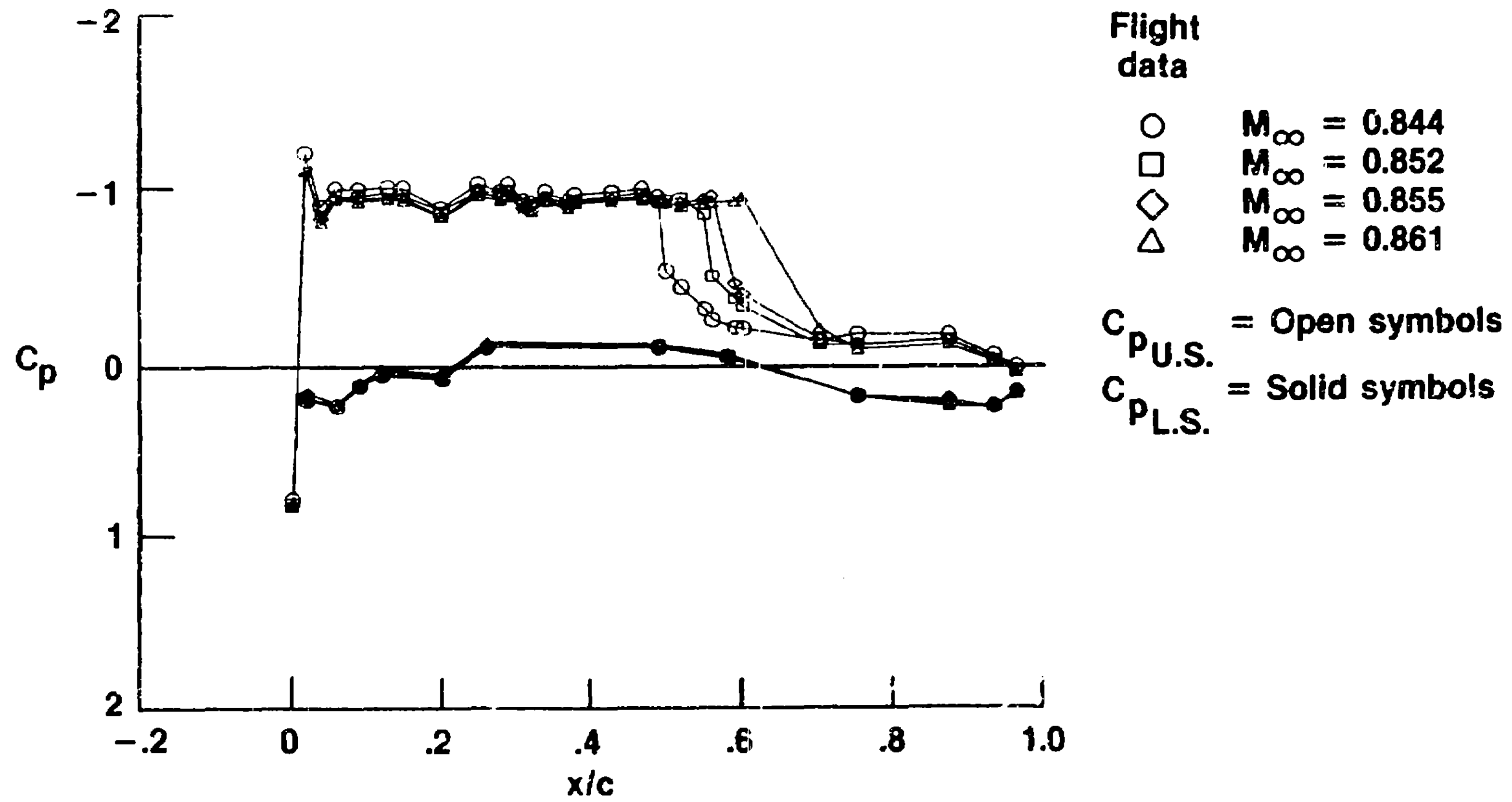
NASA AD83-865



## Effect of Small Mach Number Changes

$\eta = 0.76$, $\delta_{LE/TE} = 0/2$, and $\alpha = 8°$

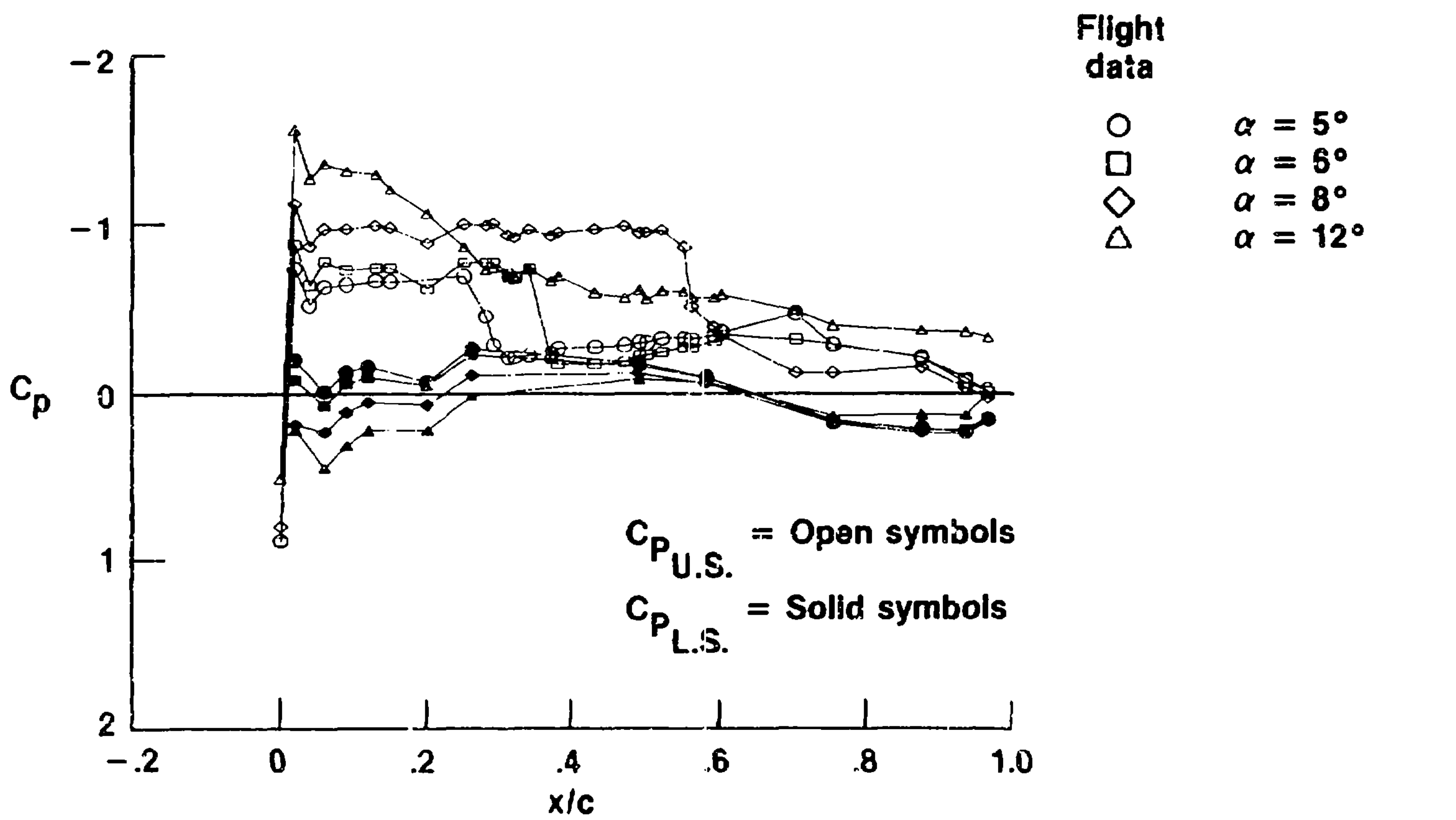
NASA AD88-873



# Effects of Angle of Attack

$\eta = 0.76$ and $M_\infty = 0.85$

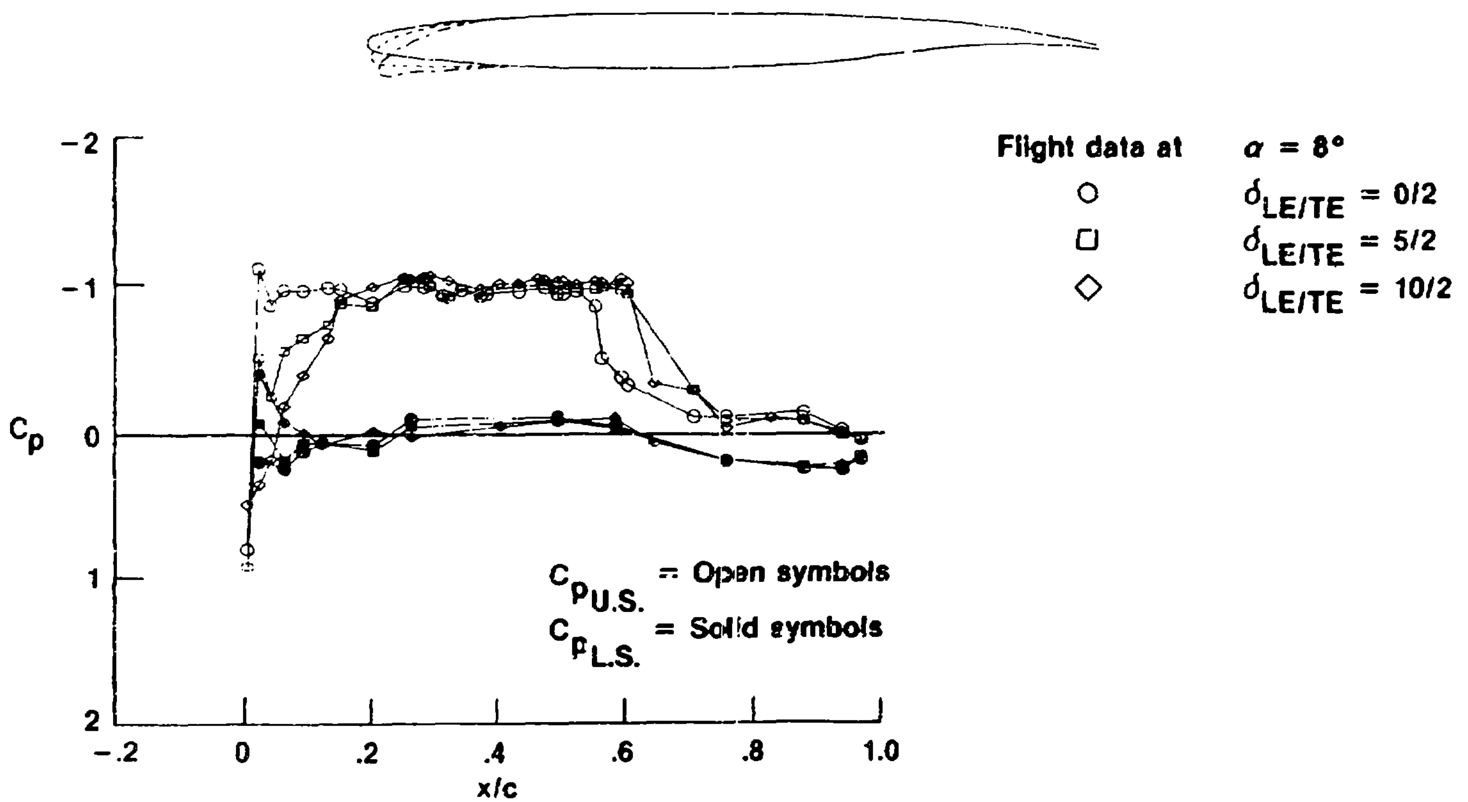
NASA AD88-932



# Effects of Three Leading-Edge Surface Deflections

NASA AD88-867

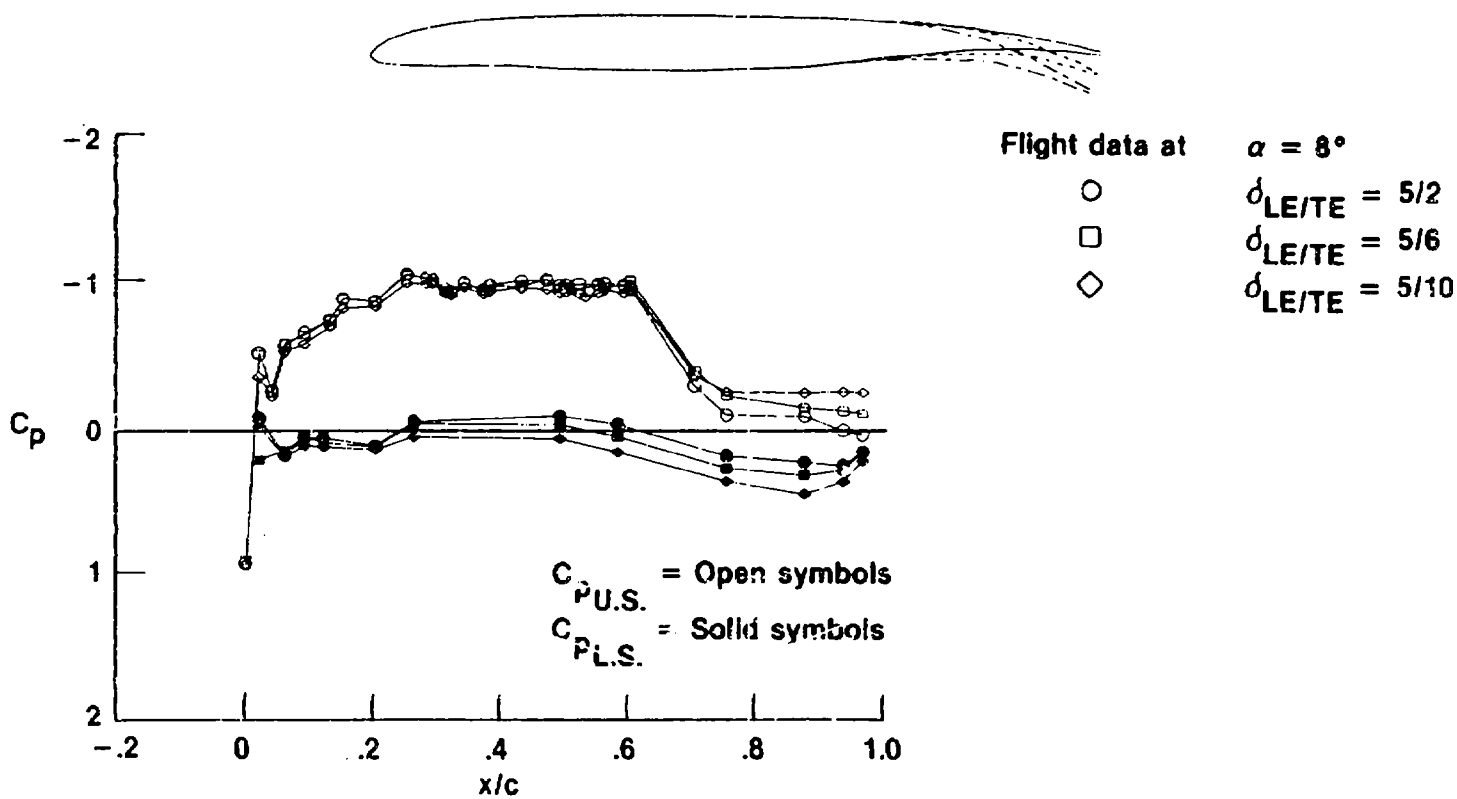
## $\eta$ = 0.76 and $M_\infty$ = 0.85



# Effects of Three Trailing-Edge Surface Deflections

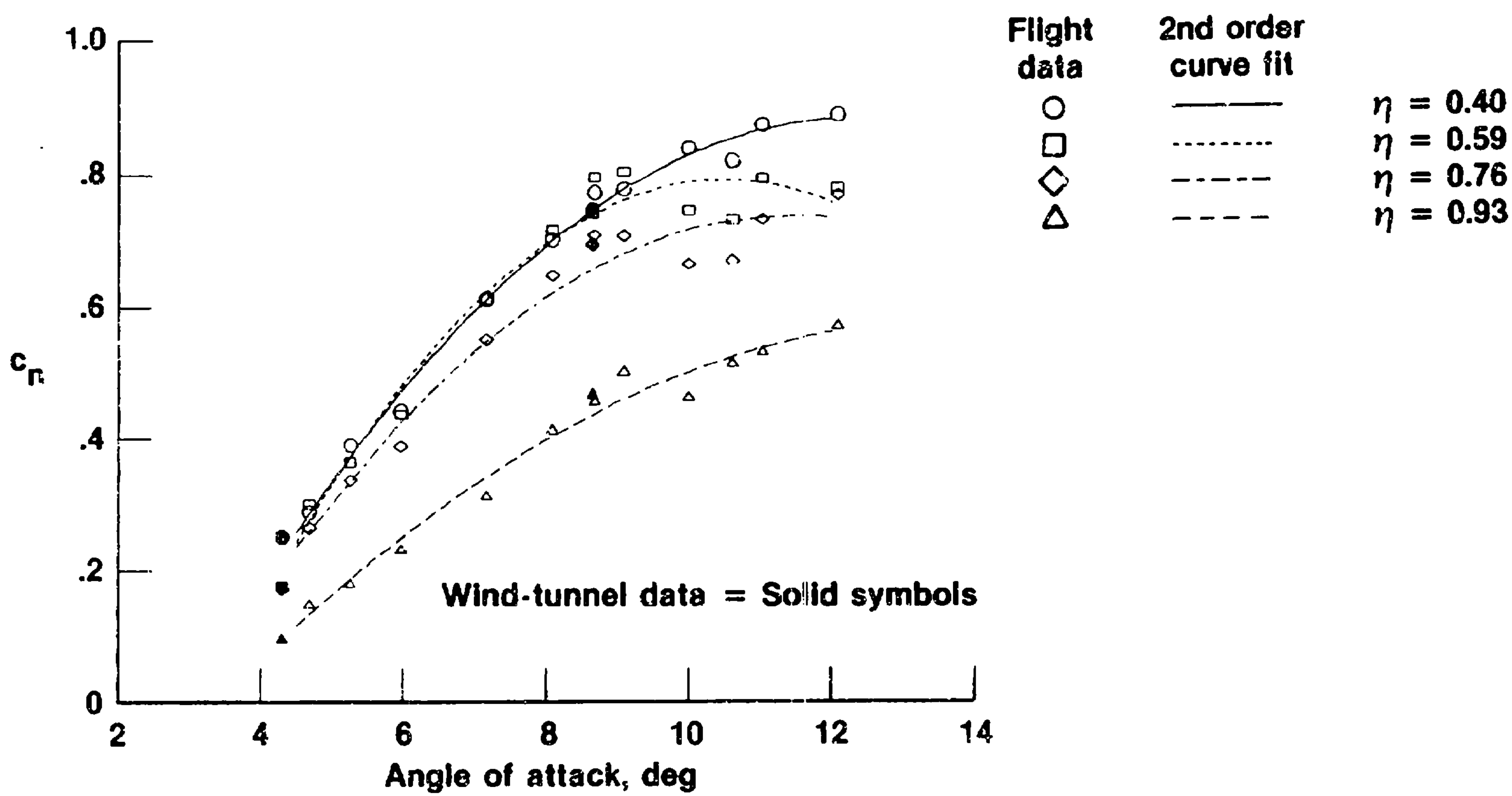
NASA
AD88-866

$\eta$ = 0.76 and $M_{\infty}$ = 0.85



# Section $c_n$ Versus $\alpha$

## $M_\infty = 0.85$ and $\delta_{LE/TE} = 0/2$

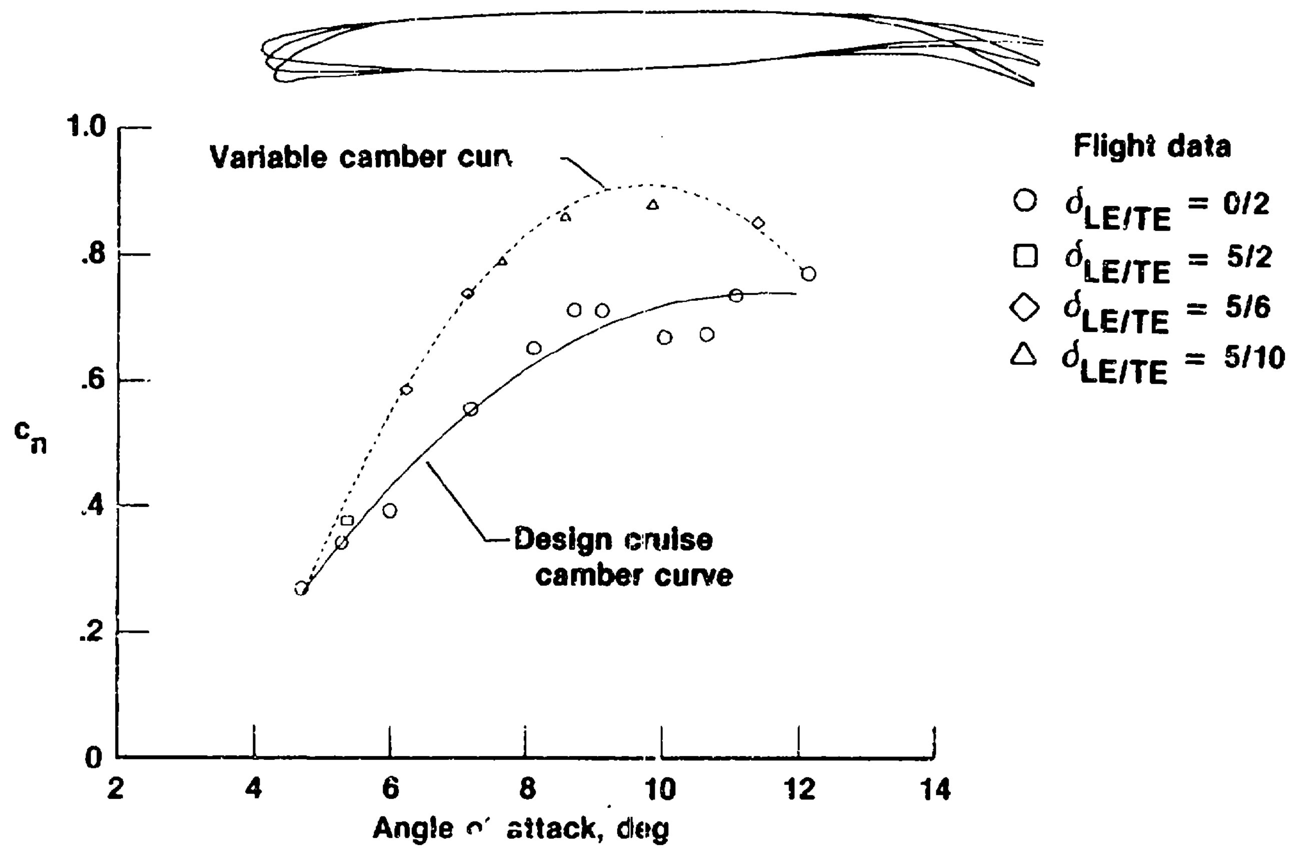



NASA AD88-931

# Camber Combinations for Optimum $c_n$ Versus $\alpha$

$\eta = 0.76$ and $M_\infty = 0.85$

AD88-868



# Transonic Airfoil Analysis

## The TAA Code

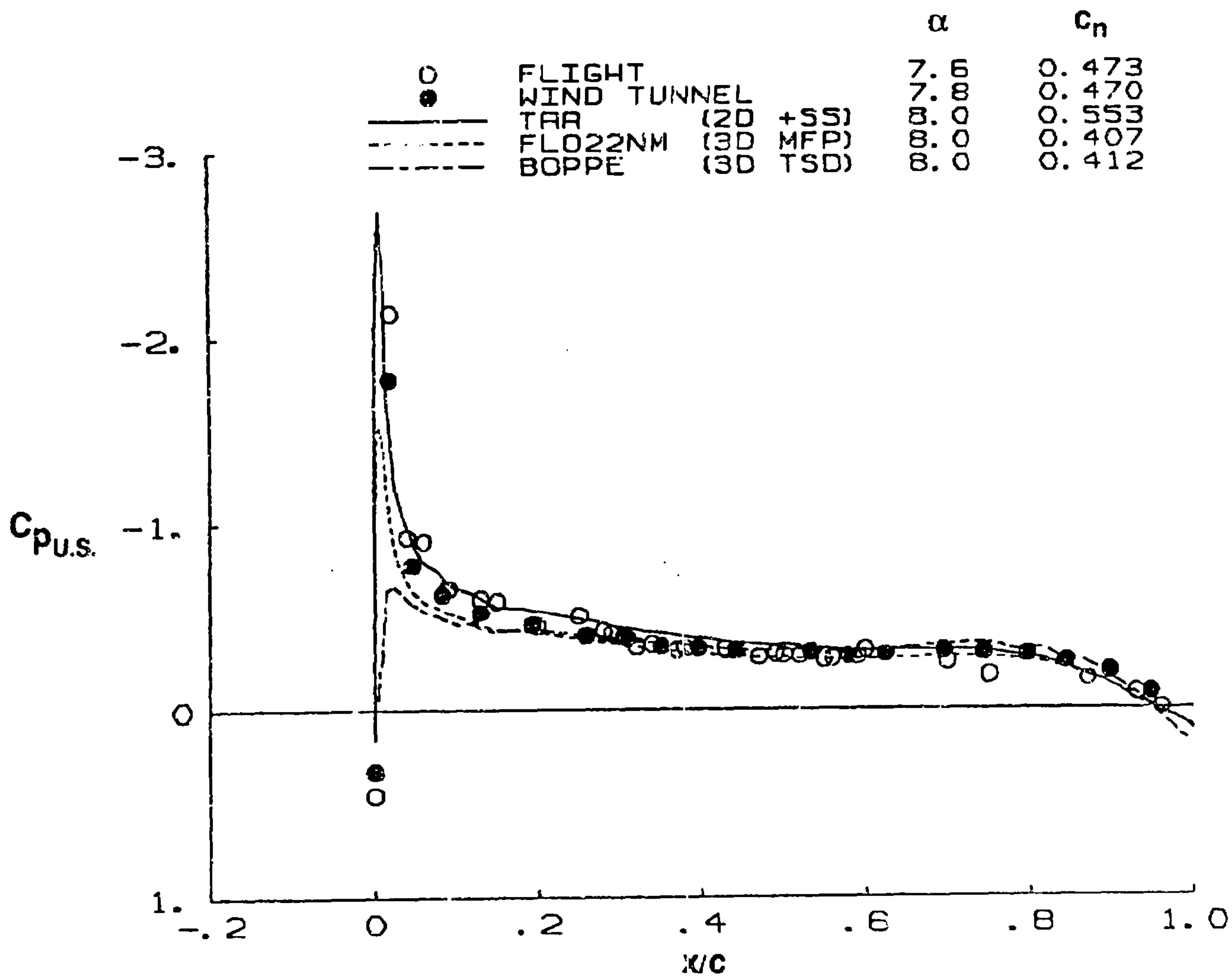
- Two-dimensional, nonconservative, full-potential flow equation with boundary layer approximation
- Mach number adjusted by simple sweep theory for three-dimensional comparison --- $M_\infty \mathrm{Cos}\Lambda_{LE}$
- Subsonic production code
- Used for TACT and MAW design analysis

## 3-D CFD Calculations in Progress

- Boppe ( transonic small disturbance theory )
- FLO 22.NM ( modified full potential theory )

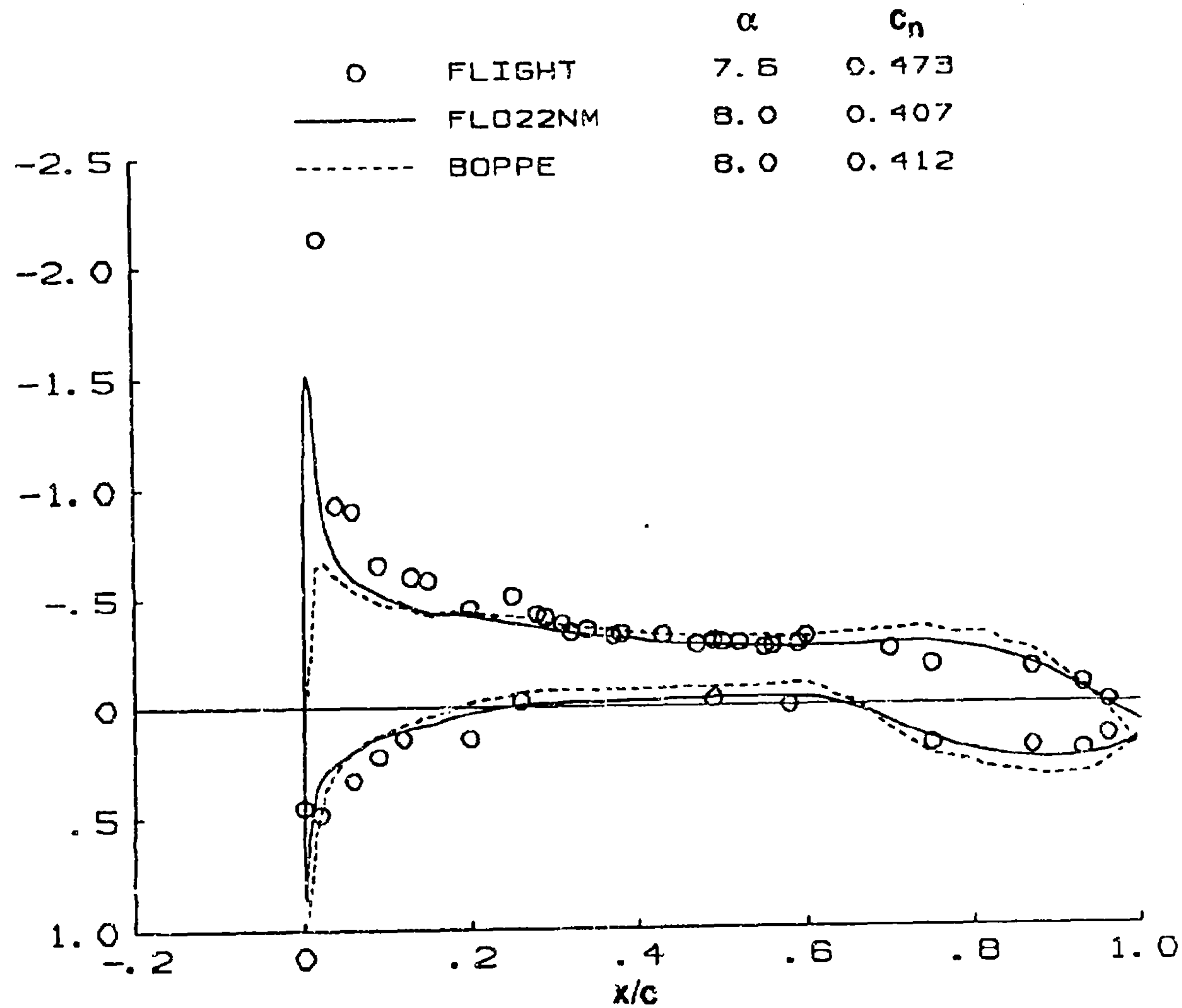
## COMPARISON OF MEASURED AND CALCULATED UPPER-SURFACE PRESSURE DISTRIBUTIONS

$\eta = 0.76$, $M_\infty = 0.60$, $\delta_{LE/TE} = 0/2$



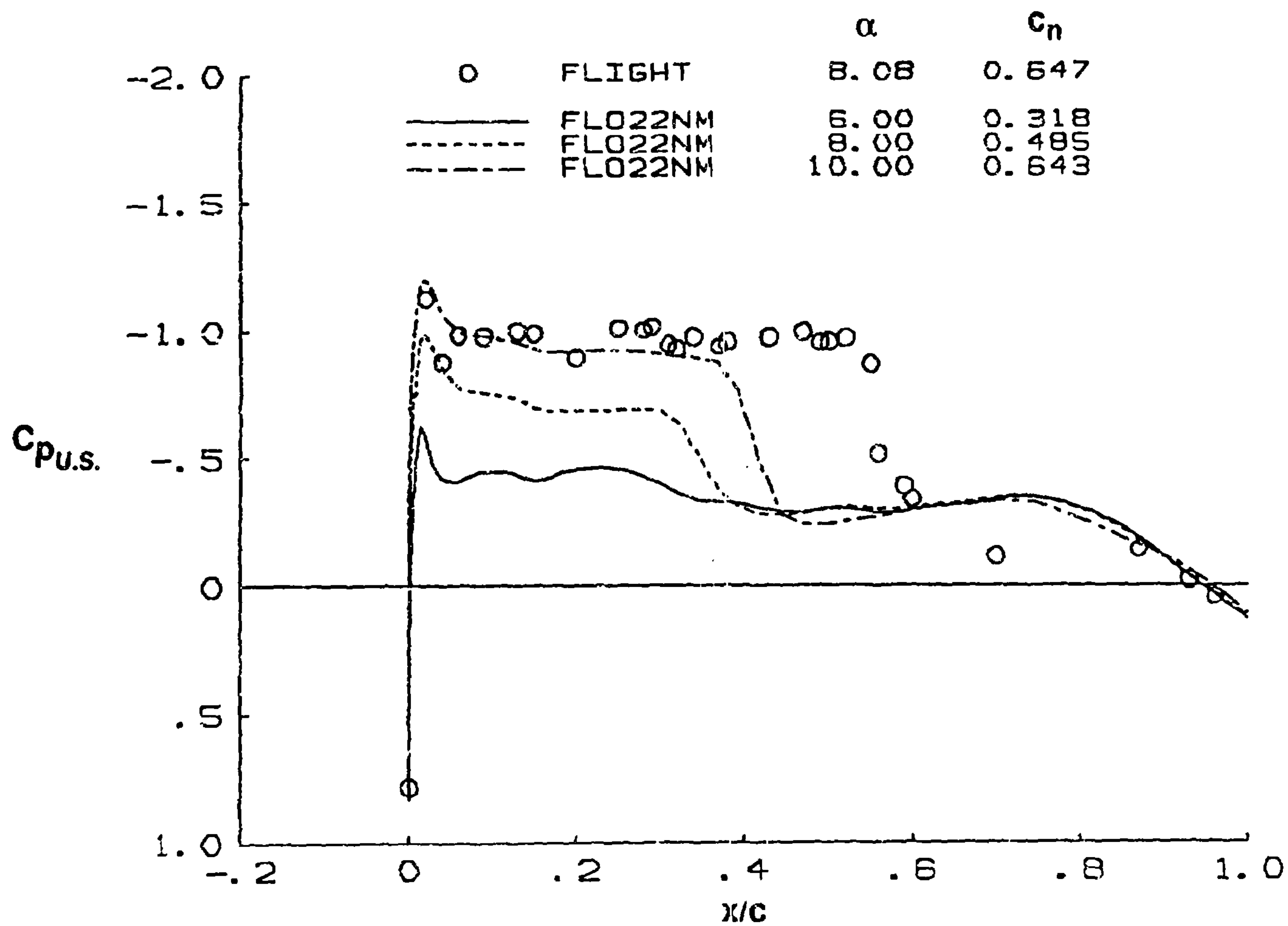
## COMPARISON OF MEASURED AND CALCULATED SURFACE PRESSURE DISTRIBUTIONS

$\eta = 0.76$, $M_\infty = 0.60$, $\delta_{LE/TE} = 0/2$



COMPARISON OF MEASURED AND CALCULATED UPPER-SURFACE PRESSURE DISTRIBUTIONS

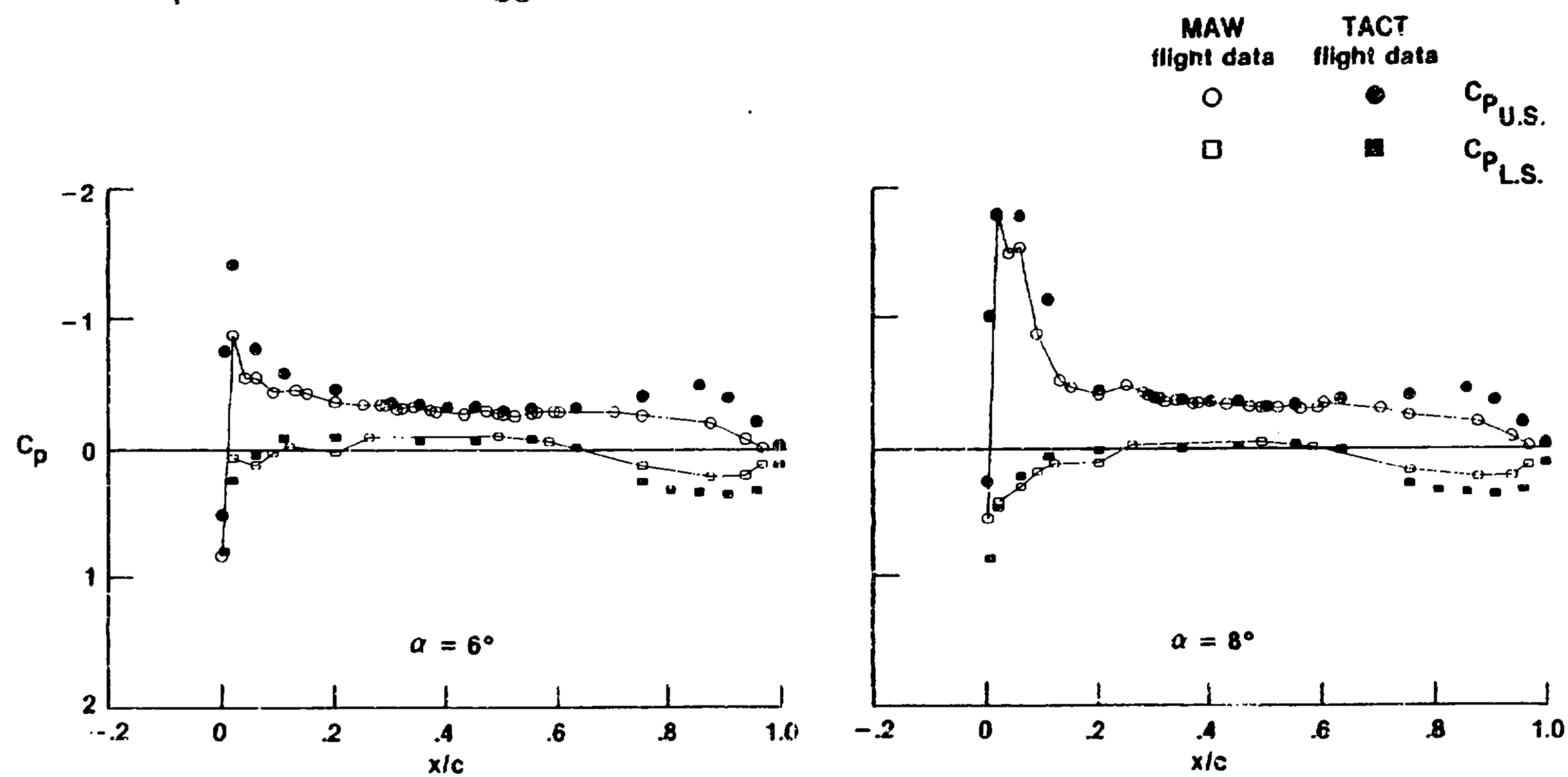
$\eta=0.76, \quad M_\infty = 0.85, \quad \delta_{LE/TE} = 0/2$



# Comparison of TACT and MAW Steady Chordwise Pressure Distributions

## $\eta = 0.76$ and $M_\infty = 0.70$

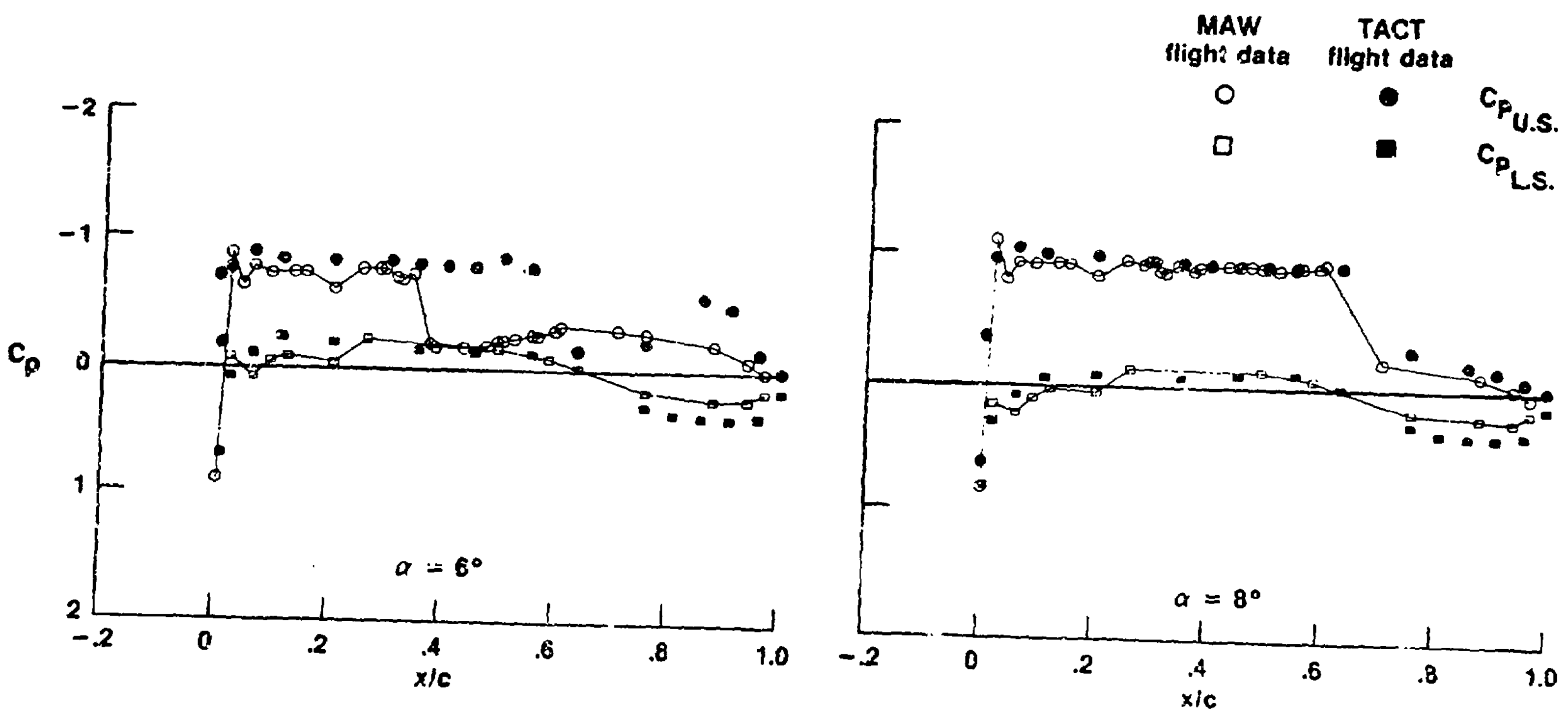
NASA AD88-871



# Comparison of TACT and MAW Steady Chord-wise Pressure Distributions

$\eta = 0.76$ and $M_{\infty} = 0.86$

NASA AD88-872



# Wing Pressure Research Remaining

- Complete some supersonic priority 2 points and repeat some priority 1 points
- Analysis data:

  effects of --- $\alpha$, $M_{\infty}$, $\delta_{LE/TE}$, $\eta$, $R_n$, $q_{\infty}$, x/c, etc.
- Compare with wind-tunnel and predicted data
- Compare wing twist data from the Flight Deflection Measurement System, to wing pressure measurements
- Final report ( including a data base )

# Concluding Remarks

- **MAW** flight data compared with wind-tunnel data
  - In general, wing pressures agreed well
- **MAW** flight data compared with **TACT** data
  - Design changes evaluated
- **MAW** chordwise pressures were integrated
  - Illustrated advantages of variable camber

# AIRCRAFT BUFFET CHARACTERISTICS

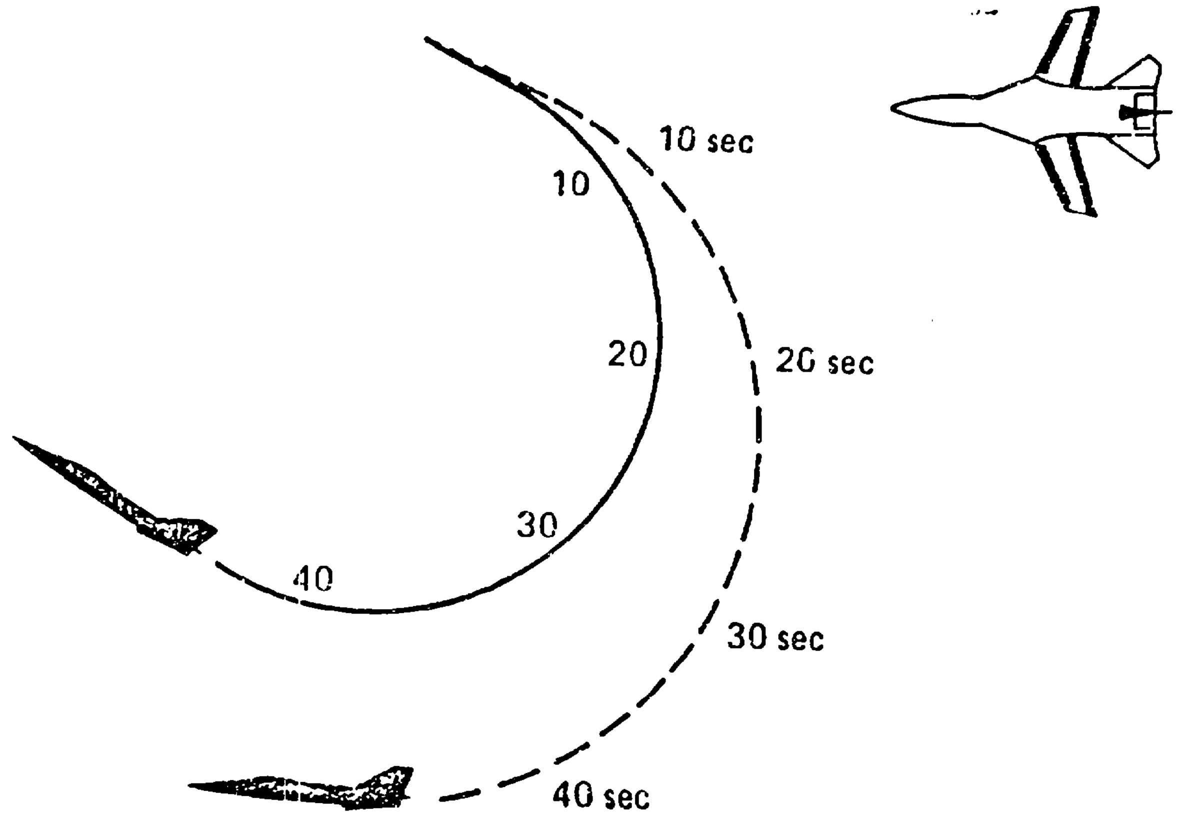
EDWARD FRIEND
NASA AMES DRYDEN

WILLIAM TOTTON
WOODSIDE SUMMIT

# Maneuver Camber Control

- AUTOMATICALLY SETS THE WING CAMBER TO OBTAIN MAXIMUM LIFT/DRAG USING TABLE LOOKUP

Conditions:
- Altitude: 25,000
- Mach: 0.7
- Sustained maneuver (33% improved)




Legend:
—— With MAW
– – – Without MAW

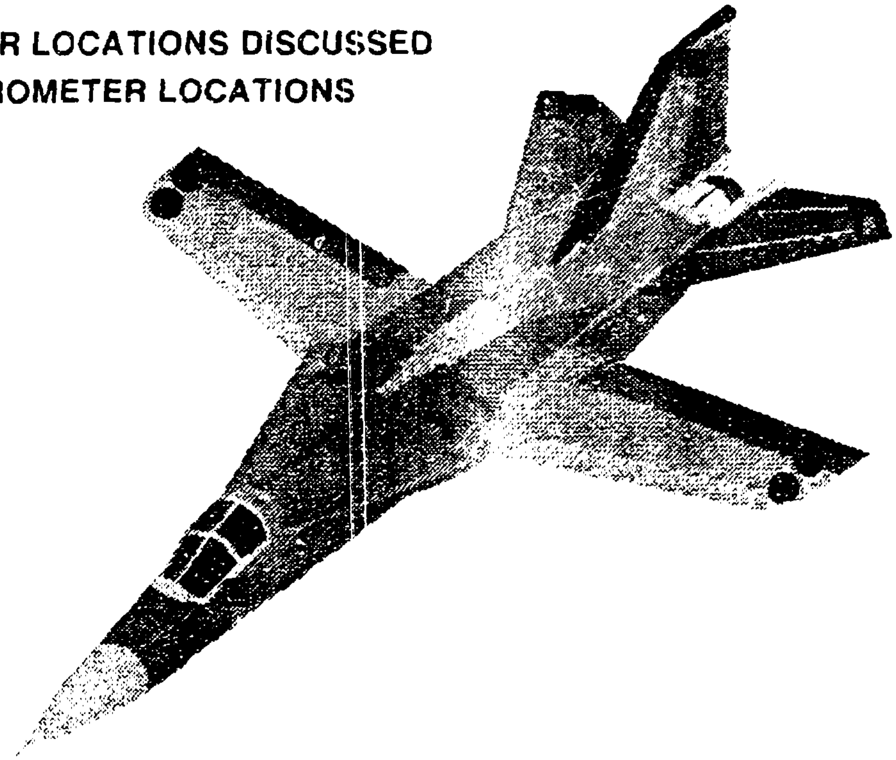
- SUSTAINED MANEUVER COMPARISON

# MAW BUFFET STUDY

- OBJECTIVES
  - DETERMINE BUFFET INTENSITY RISE (BIR) BOUNDARIES AND INTENSITY CHARACTERISTICS FOR A MATRIX OF WING-FLAP SETTINGS
  - COMPARE RESULTS WITH F-111A AND TACT FLIGHT DATA
  - COMPARE RESULTS WITH WIND TUNNEL STUDIES

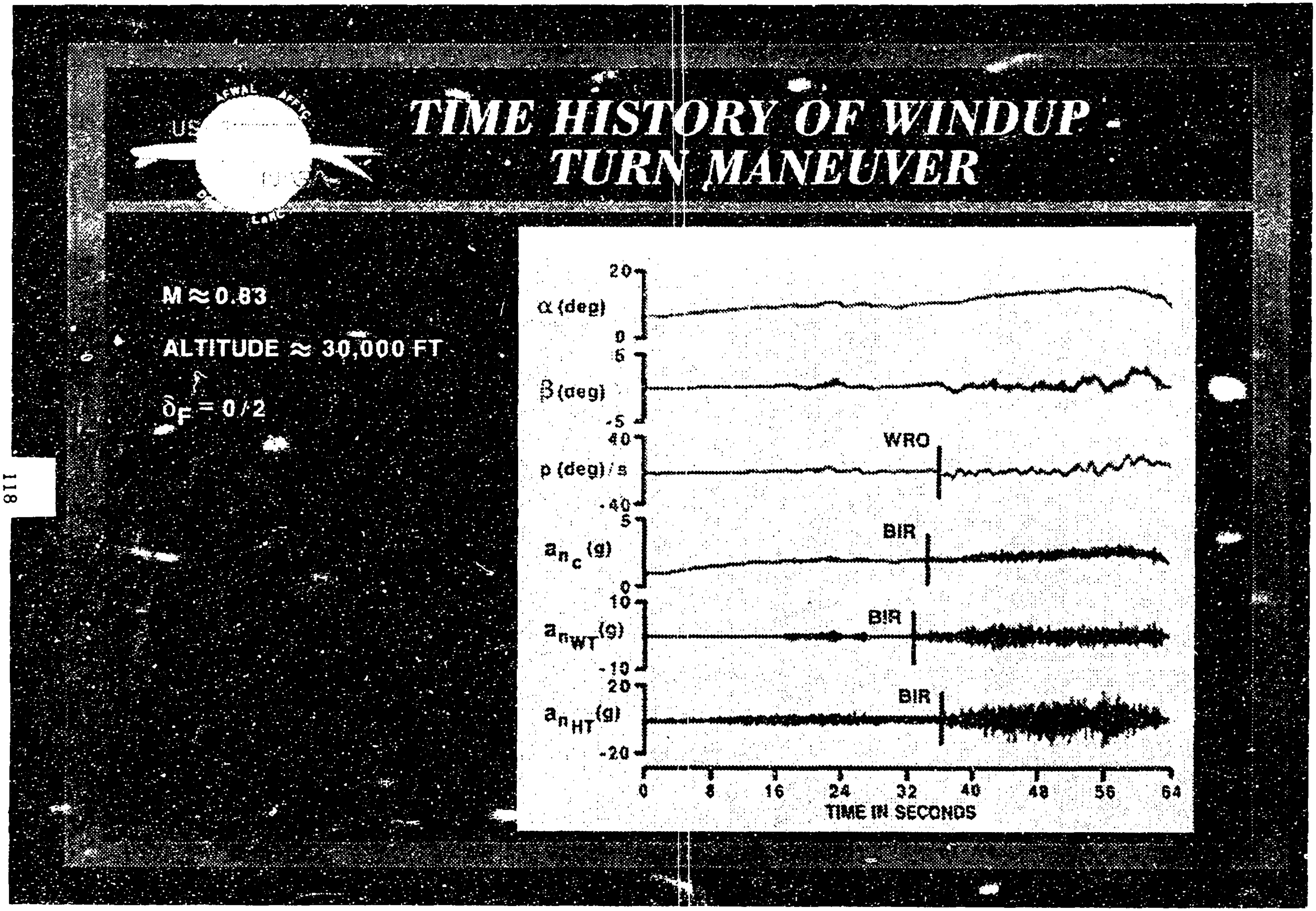
# PLANVIEW OF AFTI-F111 AIRPLANE

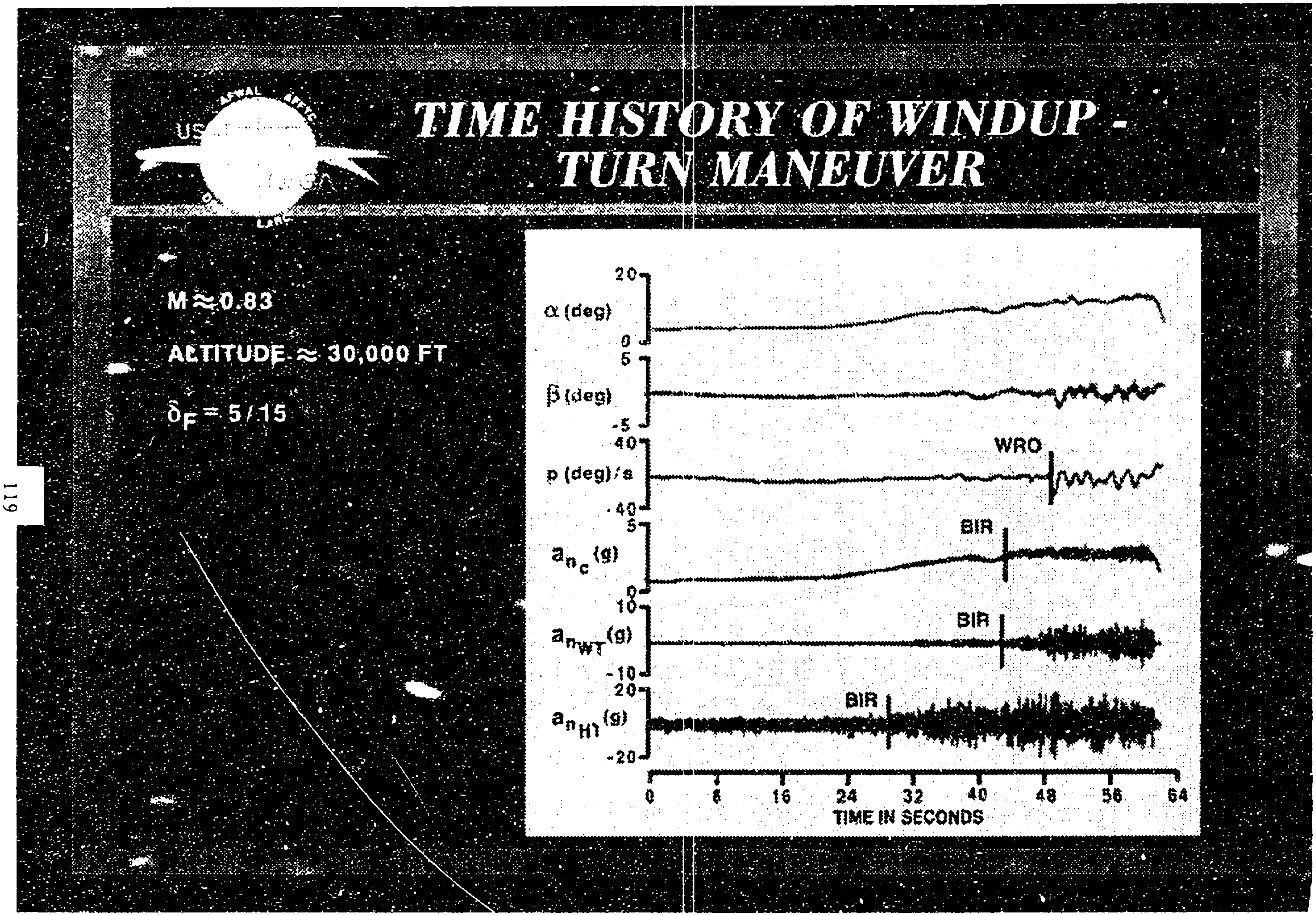
- ● ACCELEROMETER LOCATIONS DISCUSSED
- ▩ OTHER ACCELEROMETER LOCATIONS



# DATA PROCESSING

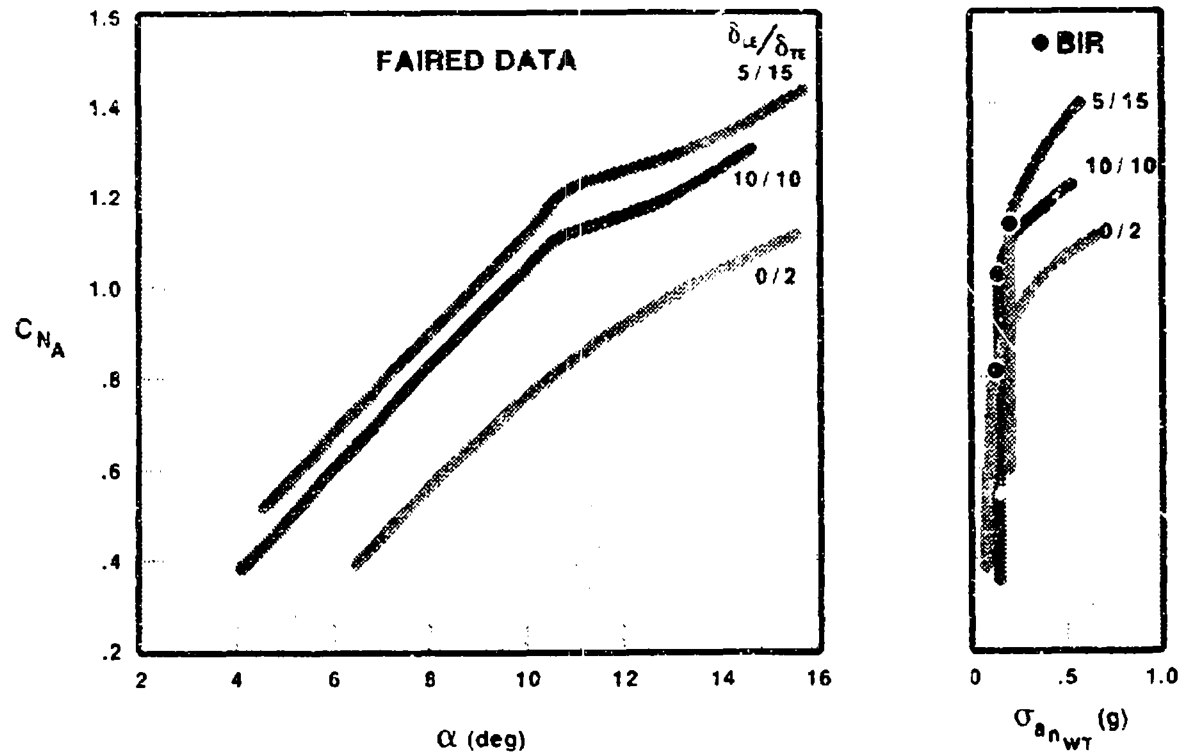
- INSTRUMENTATION
  - HIGH FREQUENCY NORMAL ACCELEROMETERS
    - WING TIP
    - HORIZONTAL TAIL TIP
    - COCKPIT
  - 160 SAMPLES PER SECOND
- DATA REDUCTION
  - EXISTING COMPUTER PROGRAM
    - DIGITAL FILTERING/RMS DATA
  - STABILITY AND CONTROL DATA LISTINGS
  - TIME HISTORIES
- GROUND TESTS
  - NATURAL FREQUENCIES OF STRUCTURE


TIME HISTORY OF WINDUP - TURN MANEUVER
M ≈ 0.83
ALTITUDE ≈ 30,000 FT
$\delta_F = 0/2$
$\alpha$ (deg)
20
0
$\beta$ (deg)
5
-5
p (deg)/s
40
-40
$a_{n_c}$ (g)
5
0
$a_{n_{WT}}$ (g)
10
-10
$a_{n_{HT}}$ (g)
20
-20
WRO
BIR
BIR
BIR
0
8
16
24
32
40
48
56
64
TIME IN SECONDS

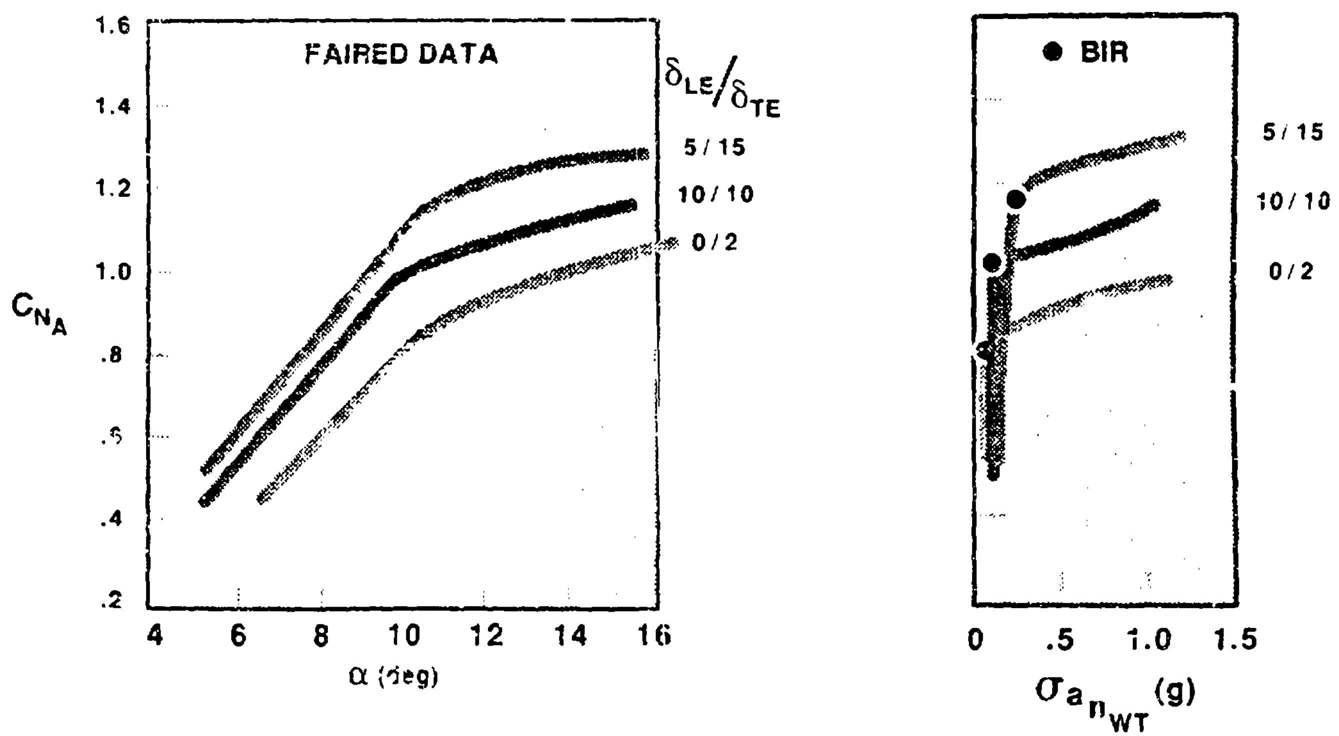

TIME HISTORY OF WINDUP - TURN MANEUVER
M ≈ 0.83
ALTITUDE ≈ 30,000 FT
$\delta_F$ = 5/15
α (deg)
β (deg)
p (deg)/s
$a_{n_c}$ (g)
$a_{n_{WT}}$ (g)
$a_{n_{H1}}$ (g)
WRO
BIR
BIR
BIR
20
0
5
-5
40
-40
5
0
10
-10
20
-20
0
8
16
24
32
40
48
56
64
TIME IN SECONDS

## VARIATION OF $C_{N_A}$ WITH ANGLE OF ATTACK AT SELECTED WING-FLAP POSITIONS

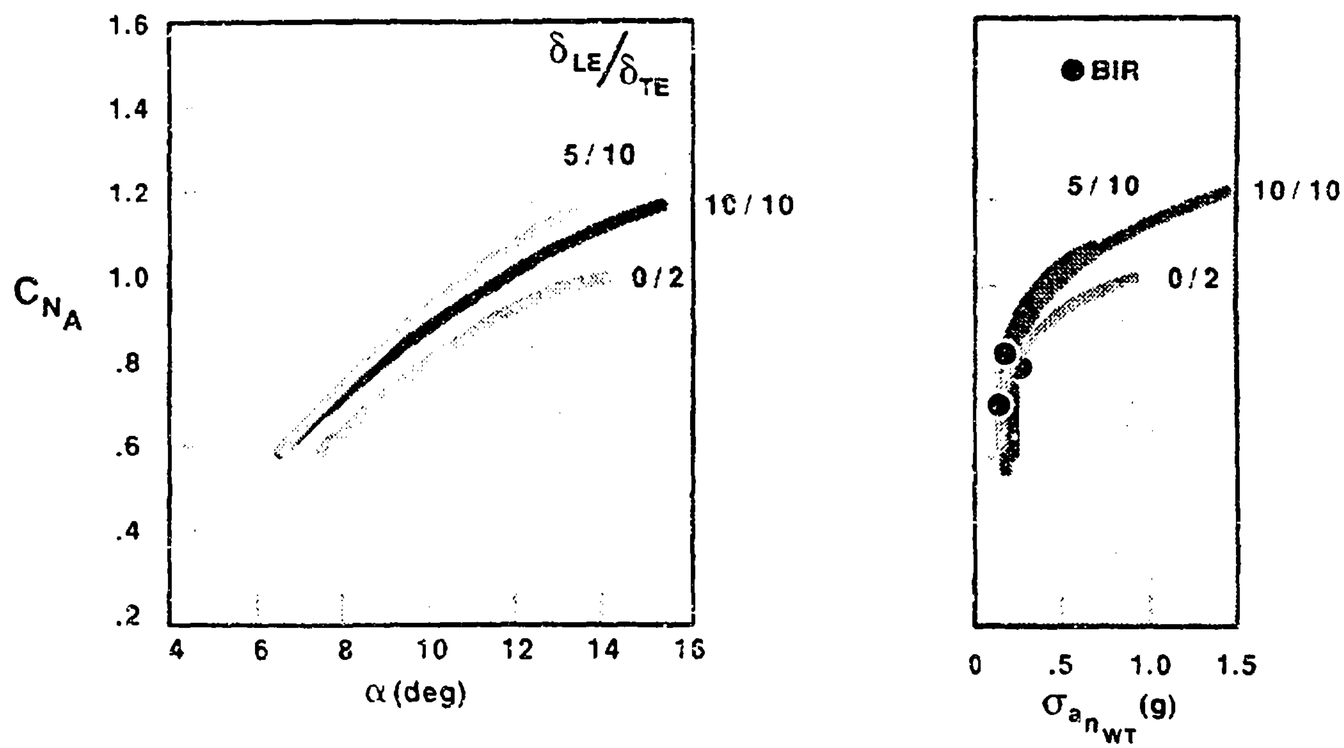
## $M \approx 0.70$, $300\ \bar{q}$



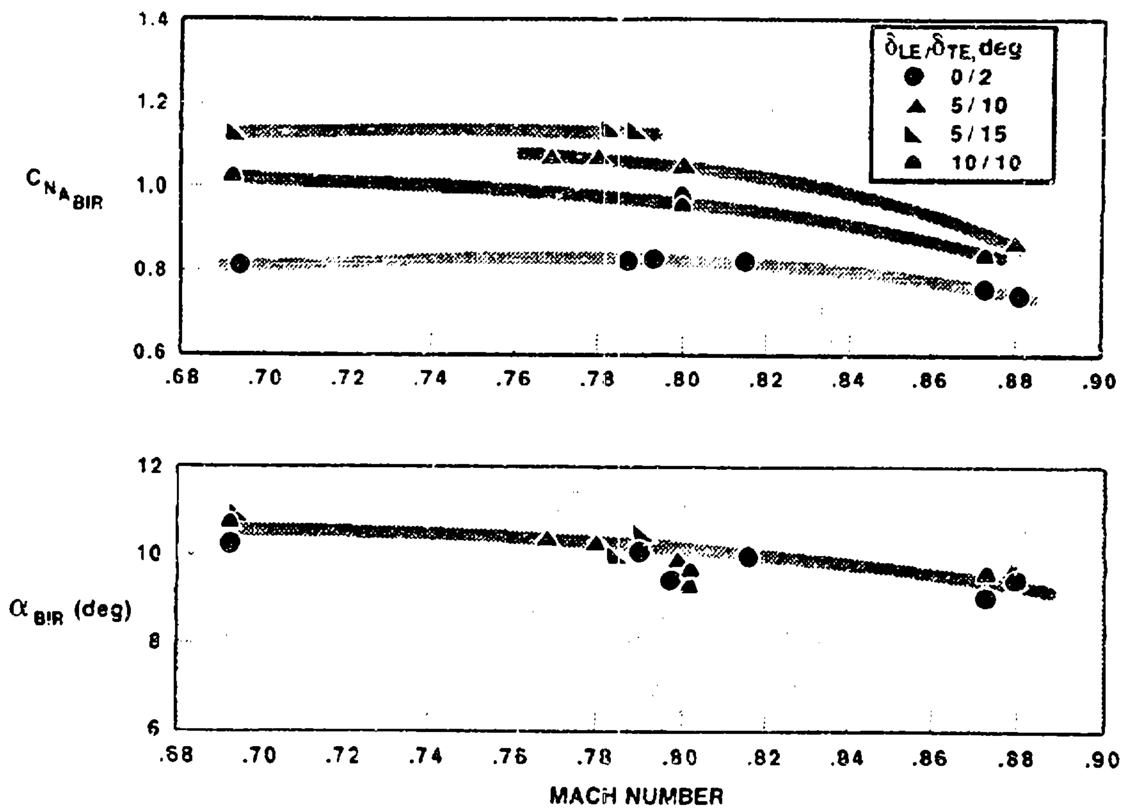
## VARIATION OF $C_{N_A}$ WITH ANGLE OF ATTACK AT SELECTED WING-FLAP POSITIONS $M \approx 0.80$, $300\ \bar{q}$



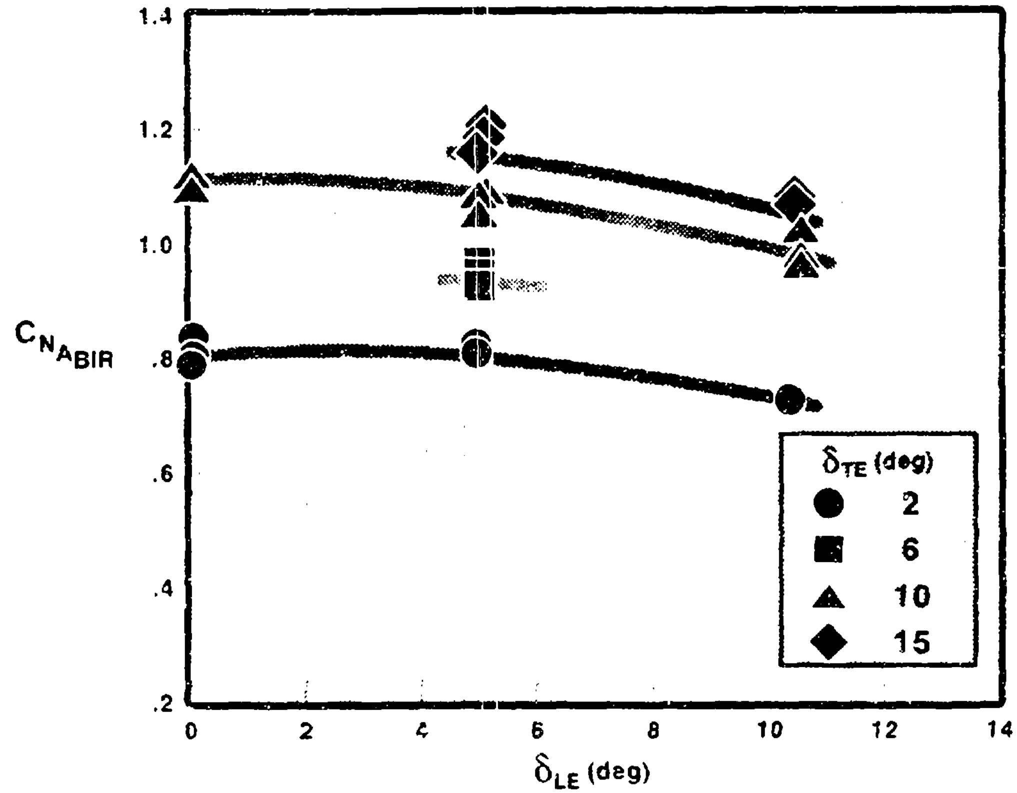
# VARIATION OF $C_{N_A}$ WITH ANGLE OF ATTACK AT SELECTED WING-FLAP POSITIONS
## $M \approx 0.88$, $300\ \overline{q}$



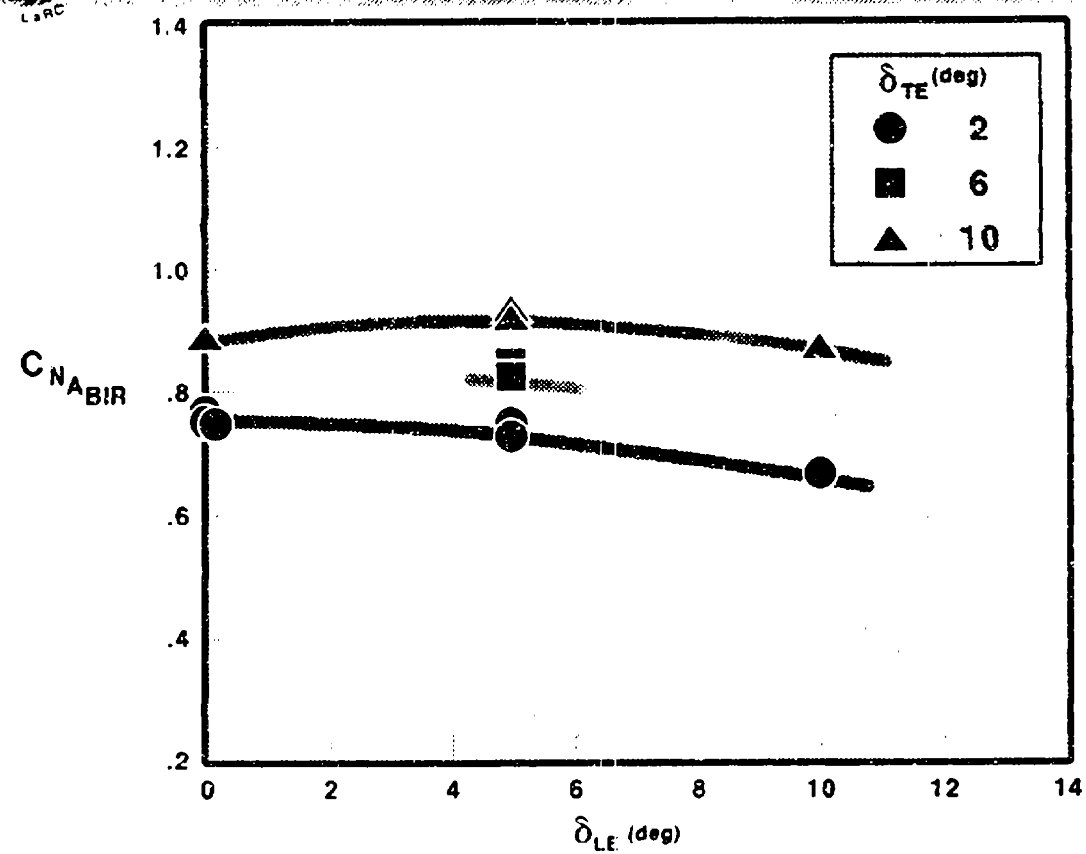
# BUFFET BOUNDARIES



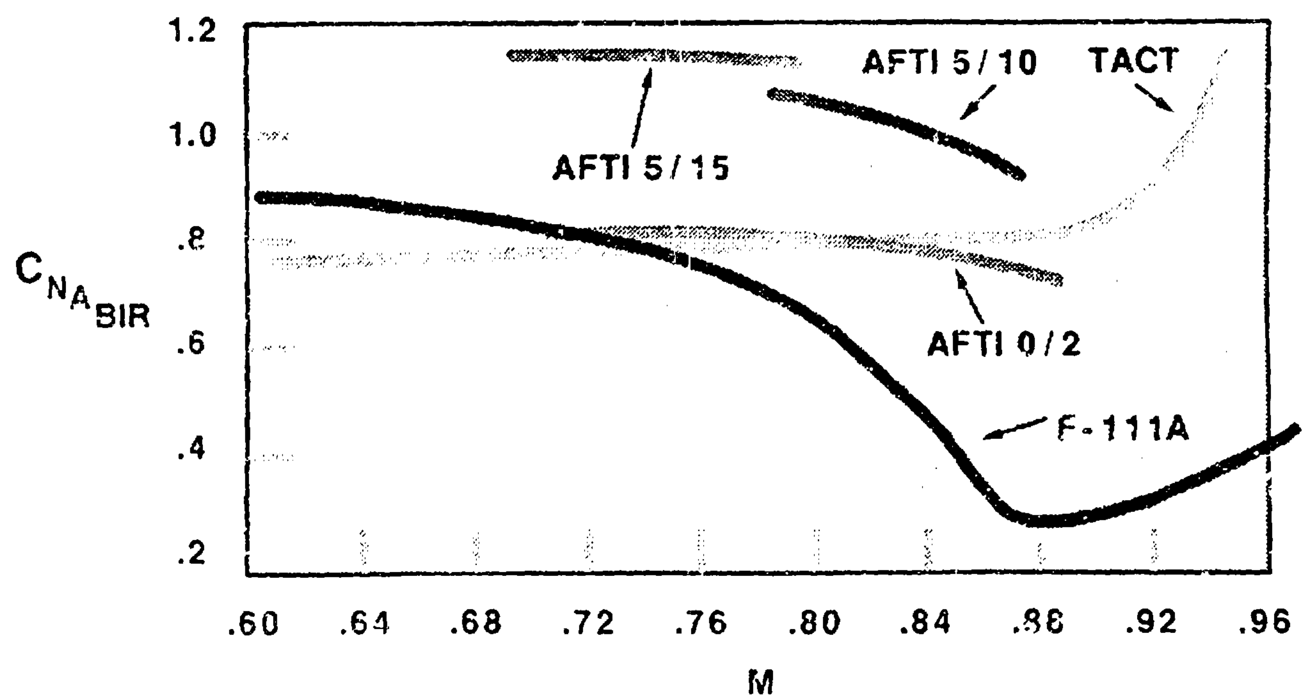
## EFFECTS OF LEADING AND TRAILING EDGE DEFLECTIONS ON THE BUFFET BOUNDARY AT $M \approx 0.80$



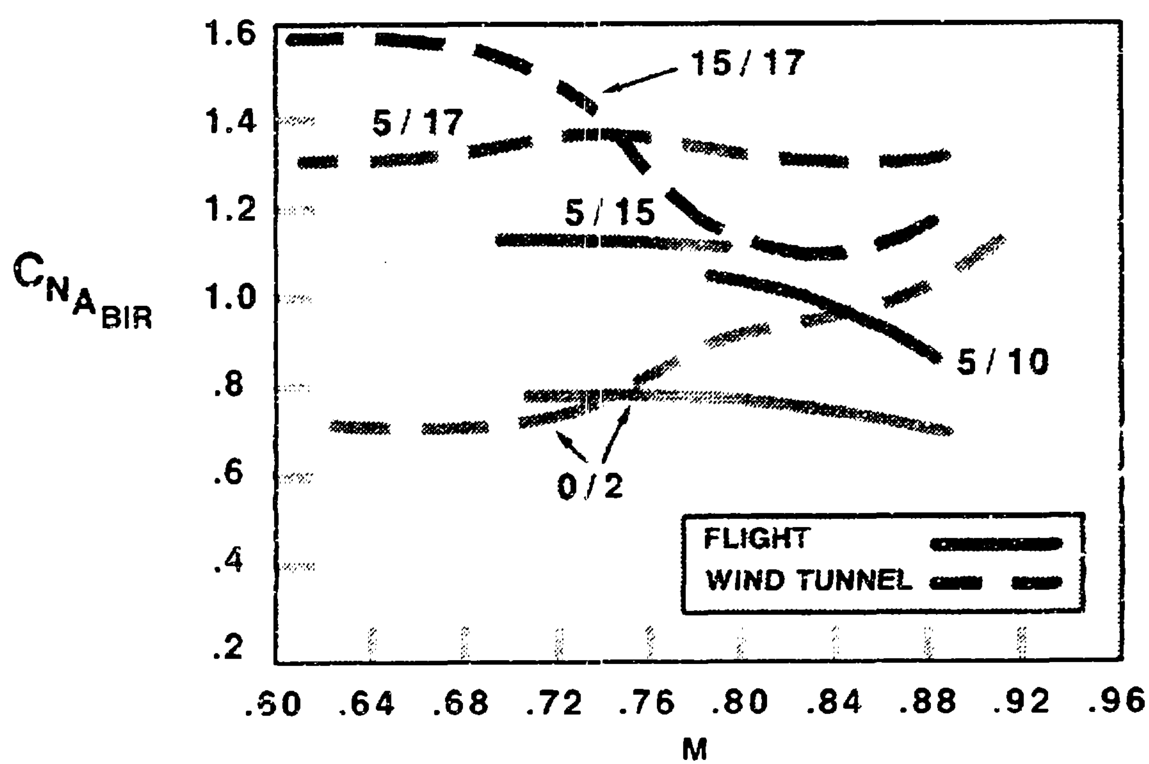
## EFFECTS OF LEADING AND TRAILING EDGE DEFLECTIONS ON THE BUFFET BOUNDARY AT $M \approx 0.88$



## BUFFET BOUNDARY SUMMARY FOR THE F-111 SERIES AIRPLANES



## COMPARISON OF FLIGHT AND WIND TUNNEL BUFFET BOUNDARIES



# CONCLUDING REMARKS

- BUFFET LEVELS EXPERIENCED WOULD BE REGARDED AS MODERATE FOR THE ENVELOPE FLOWN FOR THE BUFFET MANEUVERS (300 $\overline{q}$ FLIGHT CONDITIONS).

- THE WING-FLAP CONFIGURATIONS EVALUATED OFFER SIGNIFICANT GAINS IN THE BUFFET BOUNDARIES, BUFFET INTENSITY CHARACTERISTICS AND AIRPLANE NORMAL FORCE CURVE CHARACTERISTICS, WHEN COMPARED WITH THE CLEAN WING.

- THE BUFFET BOUNDARIES FOR THE WING-FLAP SETTINGS WHICH SHOWED THE MOST IMPROVEMENT WERE CONSIDERABLY BETTER THAN THE TACT FLIGHT DATA.

- FLIGHT BUFFET BOUNDARIES WERE GENERALLY LOWER THAN THE WIND TUNNEL DATA FOR SIMILAR WING-FLAP CONFIGURATIONS.

# SESSION III

## AUTOMATIC FLIGHT CONTROL SYSTEM DEVELOPMENT

# AFTI / F-111 MISSION ADAPTIVE WING

# AUTOMATIC FLIGHT CONTROL SYSTEM

# OBJECTIVES AND REQUIREMENTS

A. SMITCHENS
AFWAL/FIGX
21 JULY 1988

MCS 78 22?

# AGENDA

- BACKGROUND
- AFCS PROGRAM GOALS
- DOMINANT AFCS CONCERNS
- CONTROL MODE REQUIREMENTS

# BACKGROUND

- AFTI/F-111 AND AFTI/F-16 PROGRAMS
  - TECHNOLOGY INTEGRATION
  - MISSION LEVEL BENEFIT DEMONSTRATION
- SMOOTH VARIABLE CAMBER WING
  - AERODYNAMICS, LOW OBSERVABLES PAYOFFS
  - POSSIBLY, SINGLE LEADING AND TRAILING EDGE SURFACES
- CANDIDATE MISSIONS
  - BOMBERS
  - FIGHTERS
  - TRANSPORTS
- ISSUE: MAW IMPACT ON FLIGHT CONTROLS

# AFCS PROGRAM GOALS

- DEMONSTRATE MAW AND FLIGHT CONTROLS COMPATIBILITY
  - VEHICLE STABILITY AND CONTROL
  - HANDLING QUALITIES
- EXPLORE MAW AND MISSION NEED COMPATIBILITY

| | FIGHTERS | BOMBERS | TRANSPORTS |
|---|---|---|---|
| • HIGH-G MANEUVERING | X | | |
| • CONFIGURATION VARIATIONS | X | X | X |
| • WEAPON DELIVERY | X | X | |
| • LOW ALTITUDE PENETRATION | X | X | |
| • FUEL EFFICIENCY | X | X | X |

- ADVANCE CONTROLS TECHNOLOGY
  - NEW CAPABILITIES

# DOMINANT AFCS CONCERNS

- SURFACE POSITIONING PRECISION AND REPEATIBILITY
- CONTROL SYSTEM BANDWIDTH
- CONTROL POWER
- STRUCTURAL LOAD CONTROL
- RESPONSE TO SEVERAL SIMULTANEOUS CONTROL DEMANDS
- UNCERTAINTY MANAGEMENT
- NO INCREASE IN PILOTING WORKLOAD
- FLIGHT SAFETY

# CONTROL MODES

- ROLL CONTROL
- CRUISE CAMBER CONTROL
- MANEUVER LOAD CONTROL
- MANEUVER ENHANCEMENT
- GUST ALLEVIATION

SELECTABLE INDIVIDUALLY OR COLLECTIVELY

# CONTROL MODE REQUIREMENTS
# ROLL CONTROL

## PROBLEM:

- MAW/AFCS COMBINATION MAY DEGRADE A) VEHICLE STABILITY AND CONTROL OR B) FLYING QUALITIES DUE TO:
  - SURFACE POSITIONING ERRORS, HYSTERESIS
  - BANDWIDTH LIMITATIONS
  - CONTROL POWER LIMITATIONS

## REQUIREMENT

- PROVIDE MIL-F-8785B FLYING QUALITIES
- PRIORITY MODE-ALWAYS AVAILABLE
- SMOOTH AND EFFICIENT

MCS 76233

# CONTROL MODE REQUIREMENTS
# CRUISE CAMBER CONTROL

## PROBLEM:

- FUEL EFFICIENCY REQUIRES WING OPTIMALITY
- LARGE DATA BASE REQUIRED TO COVER FLIGHT ENVELOPE
- WIND TUNNEL DATA UNCERTAINTIES MAY LIMIT WING EFFICIENCY
- STORES VARIATIONS MAY COMPROMISE OPTIMALITY
- WING MANAGEMENT COULD INCREASE PILOTING WORKLOAD

## REQUIREMENT

- AUTOMATICALLY SELECT OPTIMUM LEADING AND TRAILING EDGE POSITIONS CONSISTENT WITH THE FLIGHT CONDITION
  - RAPIDLY
  - BETTER PERFORMANCE THAN TABLE LOOK-UP
  - EXTERNAL DISTURBANCE ROBUST

## CONTROL MODE REQUIREMENTS
# MANEUVER LOAD CONTROL

### PROBLEM:

- HIGH-G MANUEVERING STRUCTURAL LOADS COULD LIMIT AVAILABLE LIFT
  - WING BENDING STRESS ALLEVIATION
  - CONTROL POWER ADEQUACY

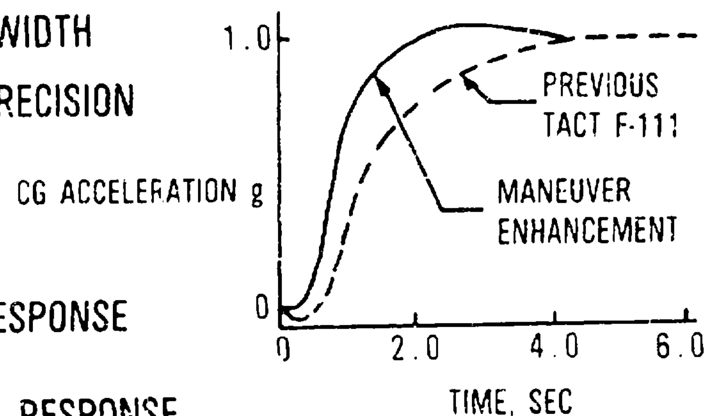
### REQUIREMENT

- SHIFT CENTER OF PRESSURE INBOARD AS A FUNCTION OF WING BENDING STRESS
- MAINTAIN MAXIMUM LIFT-TO-DRAG RATIO FOR BOTH STEADY STATE AND MANEUVERING FLIGHT

## CONTROL MODE REQUIREMENTS
# MANEUVER ENHANCEMENT

## PROBLEM:

- WEAPON DELIVERY AND OTHER FLIGHT MODES REQUIRE PRECISION ATTITUDE CONTROL
  - ACCURATE PITCH POINTING
  - CONTROL SYSTEM BANDWIDTH
  - SURFACE POSITIONING PRECISION




## REQUIREMENT

- PROVIDE QUICKENED PITCH RESPONSE
- ELIMINATE INITIAL REDUCED-G RESPONSE

MCS 78 238

# CONTROL MODE REQUIREMENTS
# GUST ALLEVIATION

## PROBLEM:

- LOW ALTITUDE PENETRATION RIDE QUALITIES MAY BE LESS THAN DESIRABLE
  - SURFACE POSITIONING PRECISION
  - CONTROL POWER
  - DYNAMIC RESPONSE

## REQUIREMENT

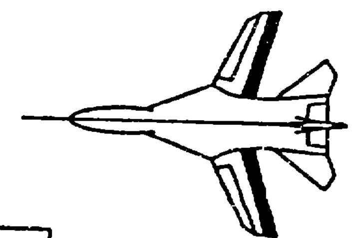
- PROVIDE DECREASED RESPONSE TO TURBULENCE REPRESENTATIVE OF THAT ENCOUNTERED IN LOW ALTITUDE PENETRATION

# CRUISE CAMBER CONTROL (CCC) MODE DEVELOPMENT

Joseph M. Hall
Boeing Advanced Systems

# Mission-Adaptive Wing

## Cruise Camber Control



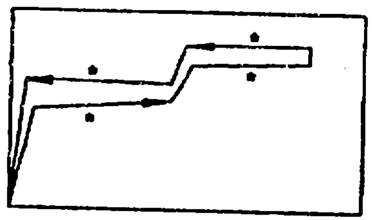
Objective: Maximize vehicle velocity during straight and level flight at constant power setting

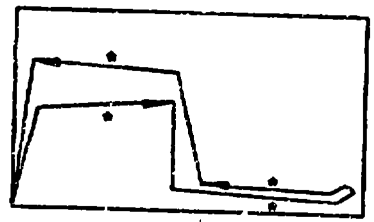
Optimization strategy:

- Perturb flap
- Measure velocity
- Use velocity measure to realize first order predictor model
- Perturb flap
- Compare measured velocity with predicted
- If predicted is less, beneficial flap change
- Reinforce beneficial flap change; otherwise reverse flap direction

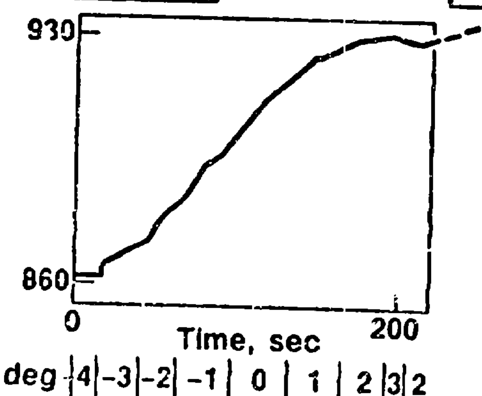
Measurements: longitudinal acceleration

Applicable mission regions:*





Performance improvement:




Future applications:

- Mission: tactical, strategic, refuel, airlift
- Aircraft: fighter, fighter bomber, long-range bomber, reconnaissance, reconnaissance-strike, tanker, cargo

# CCC MODE DEVELOPMENT SUMMARY

I INITIAL ANALYSIS AND MODE DESIGN ACCOMPLISHED WITH LINEARIZED DRAG EQUATION

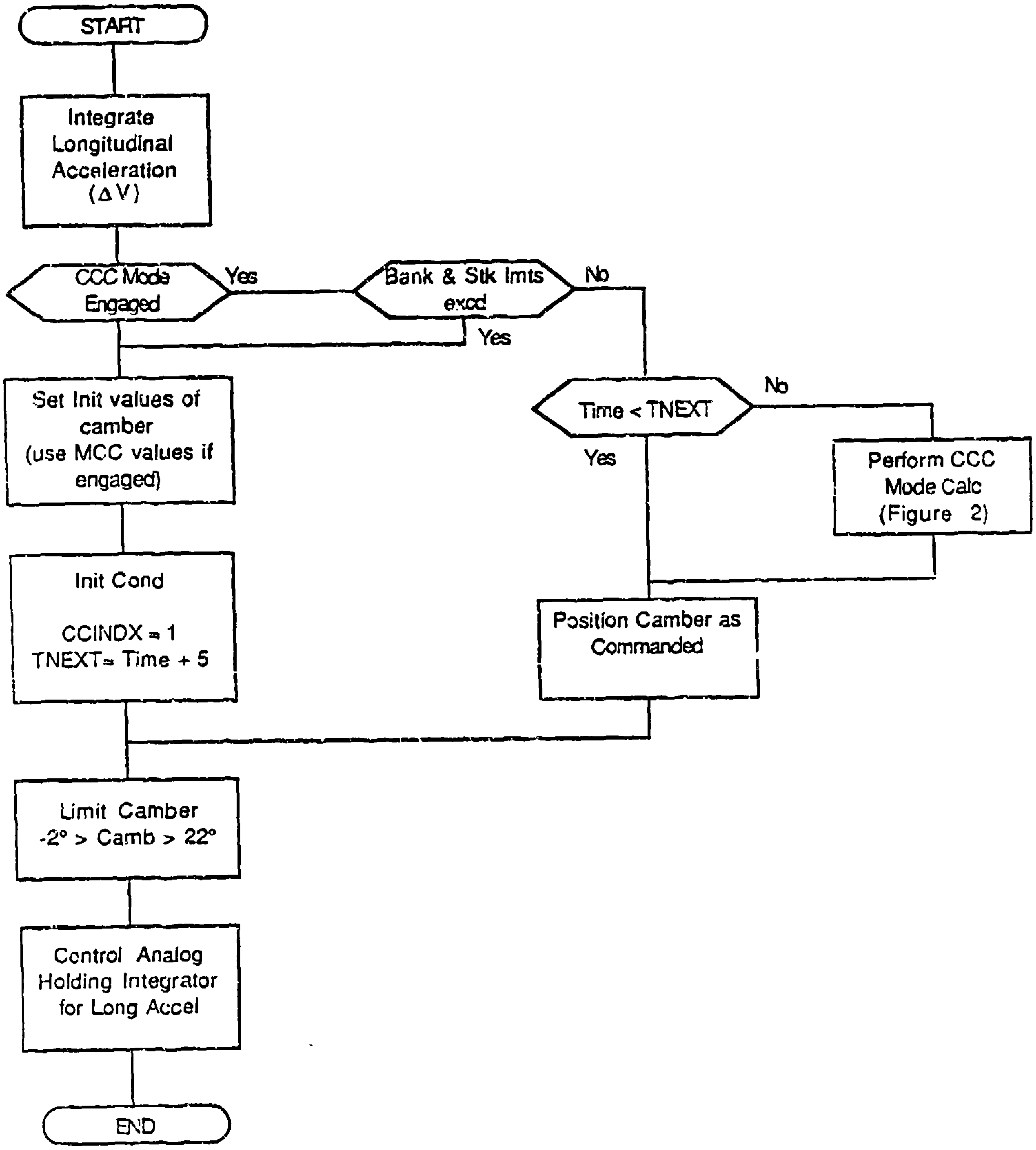
II SYSTEM PERFORMANCE VERIFIED ON 6 DOF FLIGHT SIMULATION WITH HARDWARE (FLIGHT CONTROL COMPUTERS) IN THE LOOP

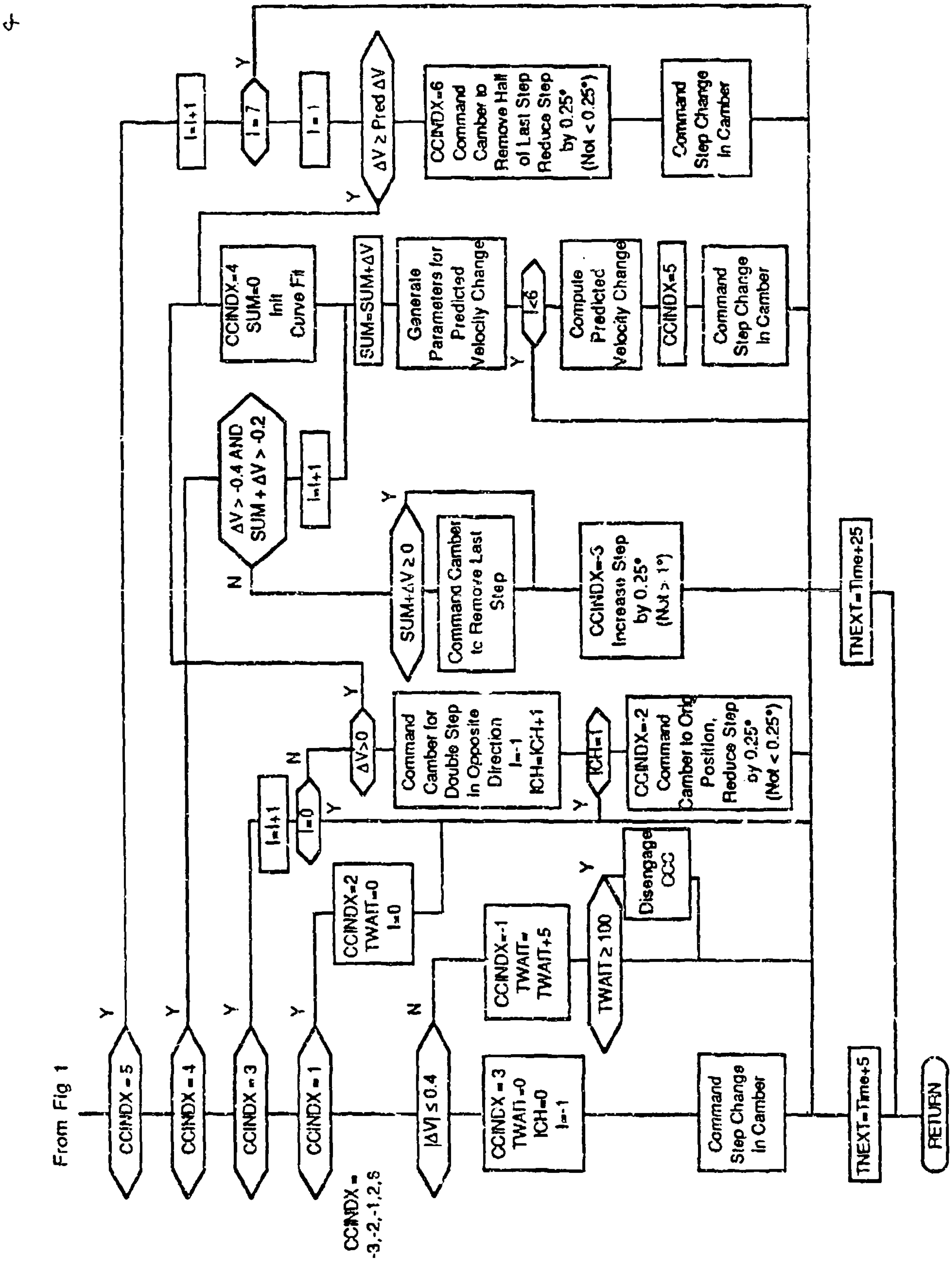
III INITIAL FLIGHT TESTING LOOKED PROMISING

IV SUBSEQUENT FLIGHT TESTING REVEALED MAJOR PROBLEMS

V REVISION OF MODE CURRENTLY IN PROGRESS

Z


START
Integrate Longitudinal Acceleration ($\Delta$V)
CCC Mode Engaged
Yes
Bank & Stk lmts excd
No
Yes
Set Init values of camber (use MCC values if engaged)
Time < TNEXT
No
Yes
Perform CCC Mode Calc (Figure 2)
Init Cond
CCINDX = 1
TNEXT = Time + 5
Position Camber as Commanded
Limit Camber -2° > Camb > 22°
Control Analog Holding Integrator for Long Accel
END



From Fig 1
CCINDX = 5
CCINDX = 4
CCINDX = 3
CCINDX = 1
CCINDX = -3,-2,-1,2,6
|ΔV| ≤ 0.4
CCINDX = 3 TWAIT=0 ICH=0 I=-1
Command Step Change In Camber
TNEXT=Time+5
RETURN
CCINDX=2 TWAIT=0 I=0
CCINDX=-1 TWAIT= TWAIT+5
TWAIT ≥ 100
Disengage CCC
I=I+1
I=0
ΔV>0
Command Camber for Double Step In Opposite Direction I=-1 ICH=ICH+1
ICH=1
CCINDX=-2 Command Camber to Orig Position, Reduce Step by 0.25° (Not < 0.25°)
ΔV > -0.4 AND SUM + ΔV > -0.2
I=I+1
SUM+ΔV ≥ 0
Command Camber to Remove Last Step
CCINDX=-3 Increase Step by 0.25° (Not > 1°)
TNEXT=Time+25
CCINDX=4 SUM=0 Init Curve Fit
SUM=SUM+ΔV
Generate Parameters for Predicted Velocity Change
I<6
Compute Predicted Velocity Change
CCINDX=5
Command Step Change In Camber
I=I+1
I=7
I=1
ΔV ≥ Pred ΔV
CCINDX=6 Command Camber to Remove Half of Last Step Reduce Step by 0.25° (Not < 0.25°)
Command Step Change In Camber
Y
N

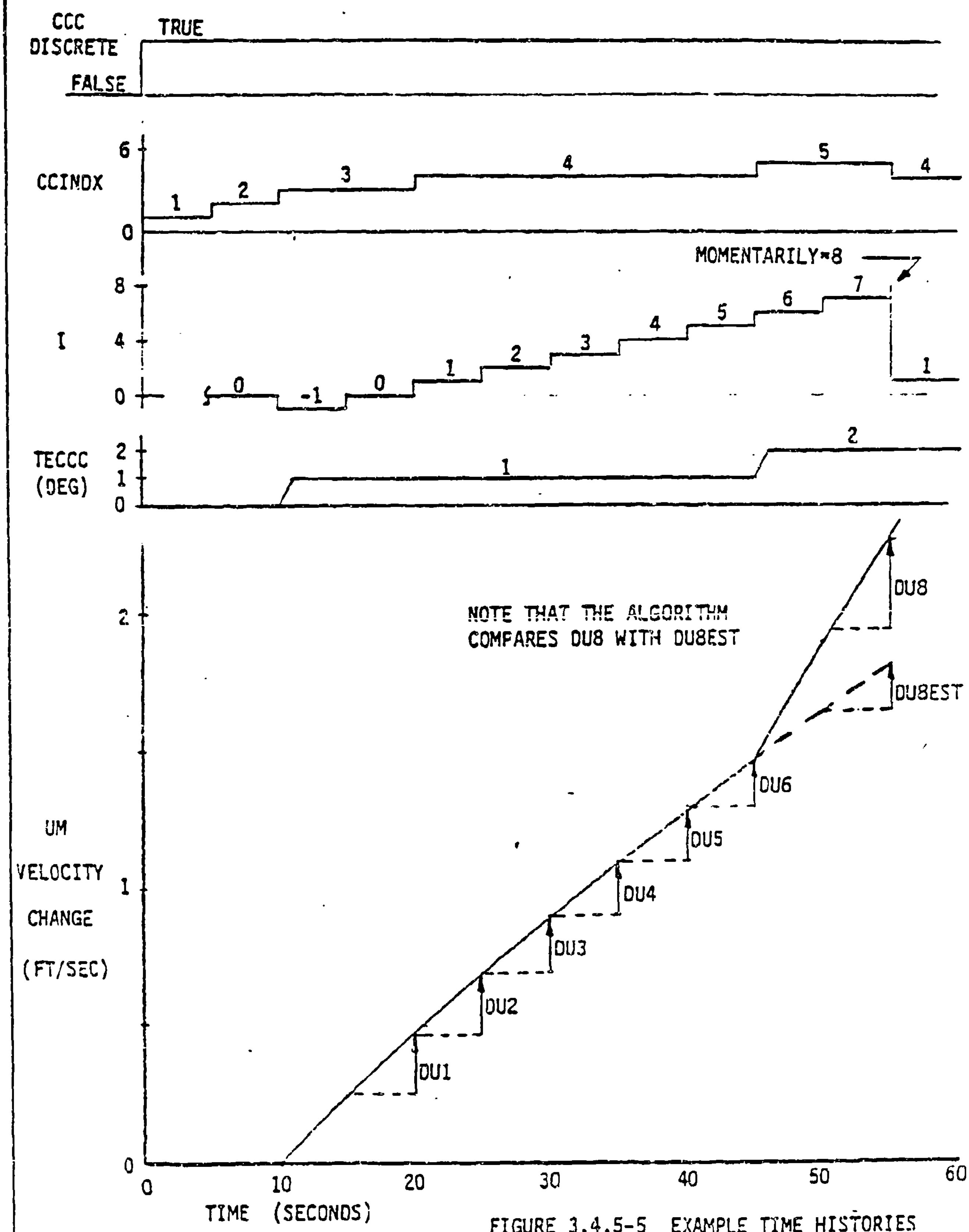
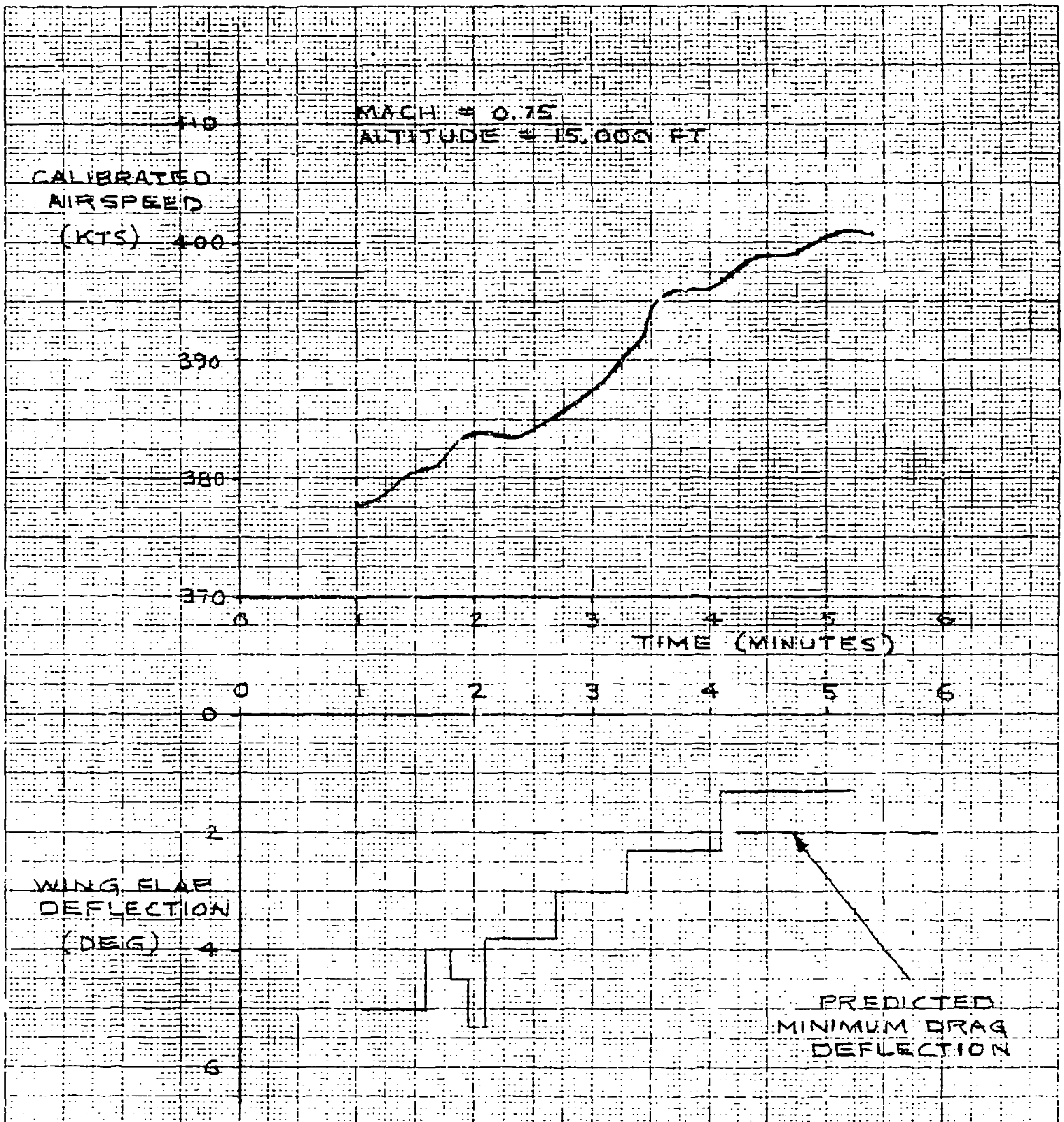



FIGURE 3.4.5-5 EXAMPLE TIME HISTORIES




CRUISE CAMBER CONTROL
PERFORMANCE

9

# CCC MODE FUTURE PLANS

I EVALUATE THE USE OF AIRSPEED INSTEAD OF LONGITUDINAL ACCELERATION ON THE FLIGHT SIMULATOR

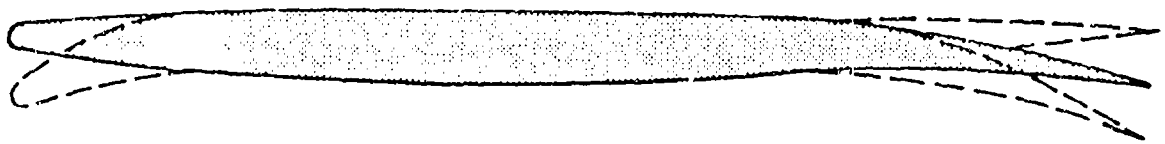
II REVISE THE CCC SOFTWARE TO IMPLEMENT THIS CHANGE

III FLIGHT TEST THE REVISED SYSTEM

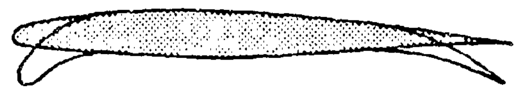
# MANEUVER CAMBER CONTROL (MCC) MODE DEVELOPMENT

George E. Lewis
Boeing Advanced Systems

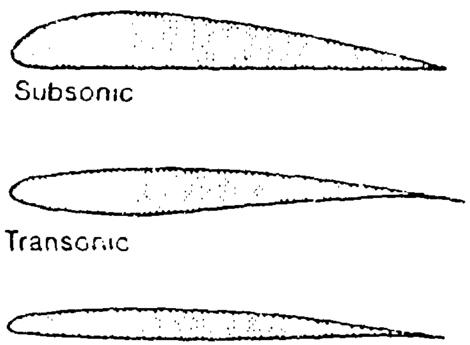
# MAW: An Efficient Shape for All Flight Conditions

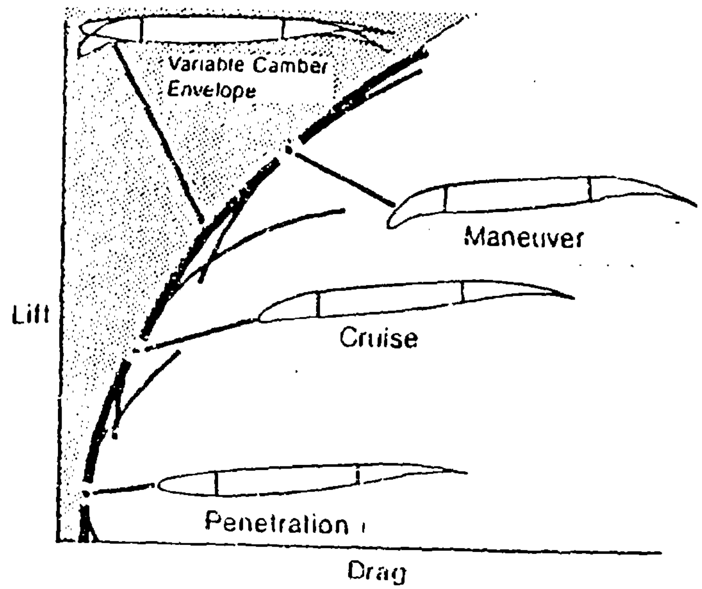


Mission Adaptive Wing,
One Wing for All Conditions



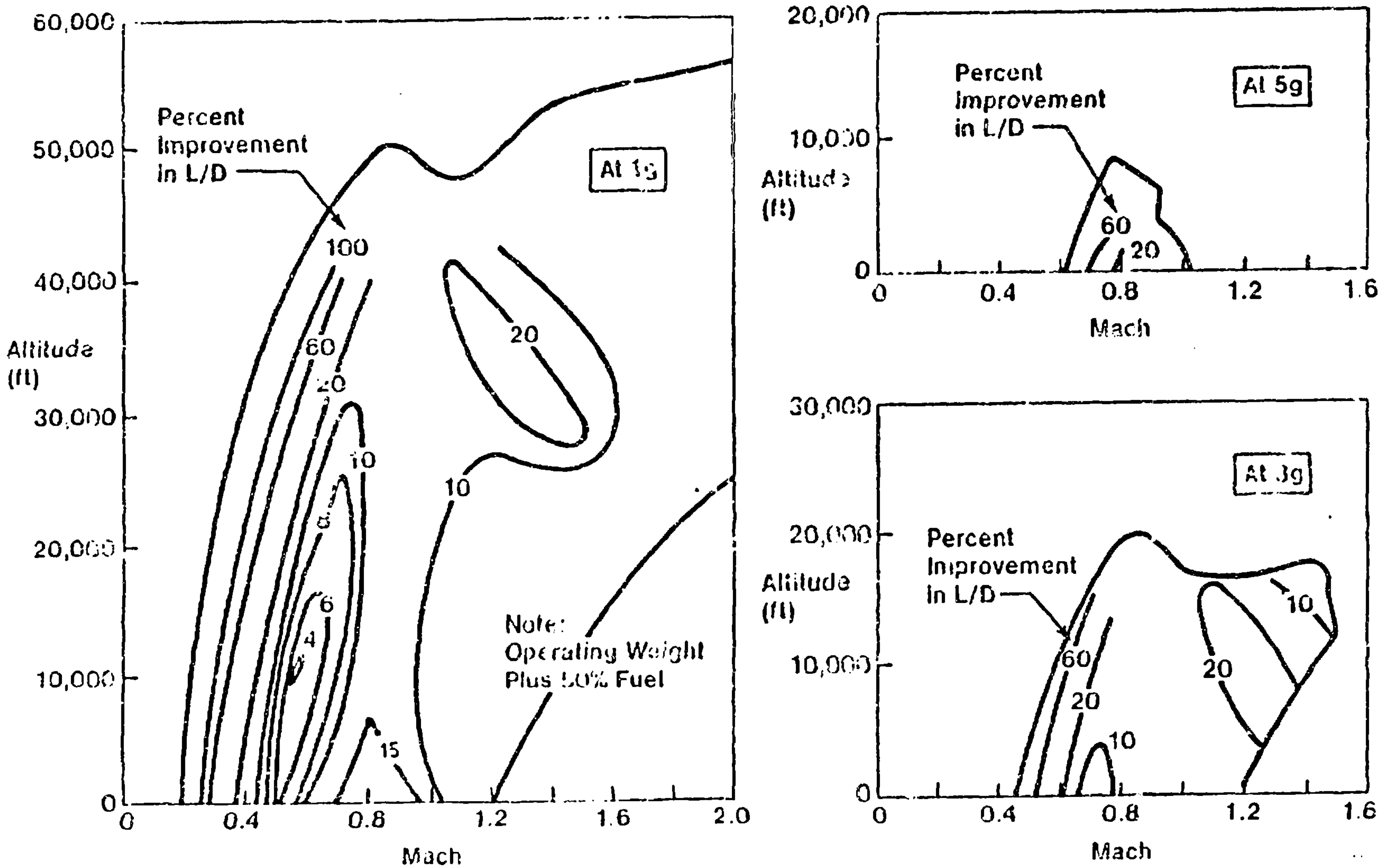
Conventional Wings



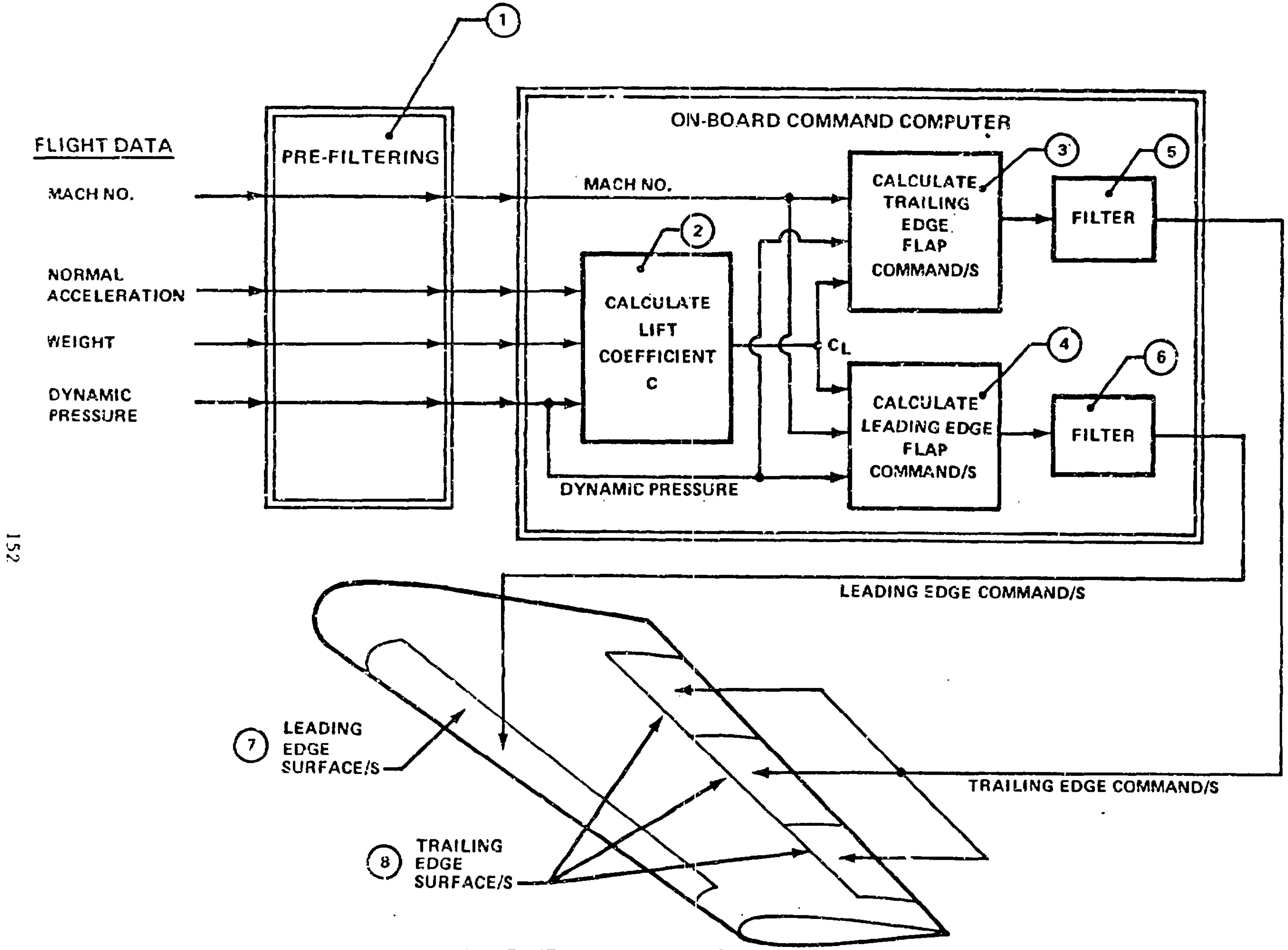




4

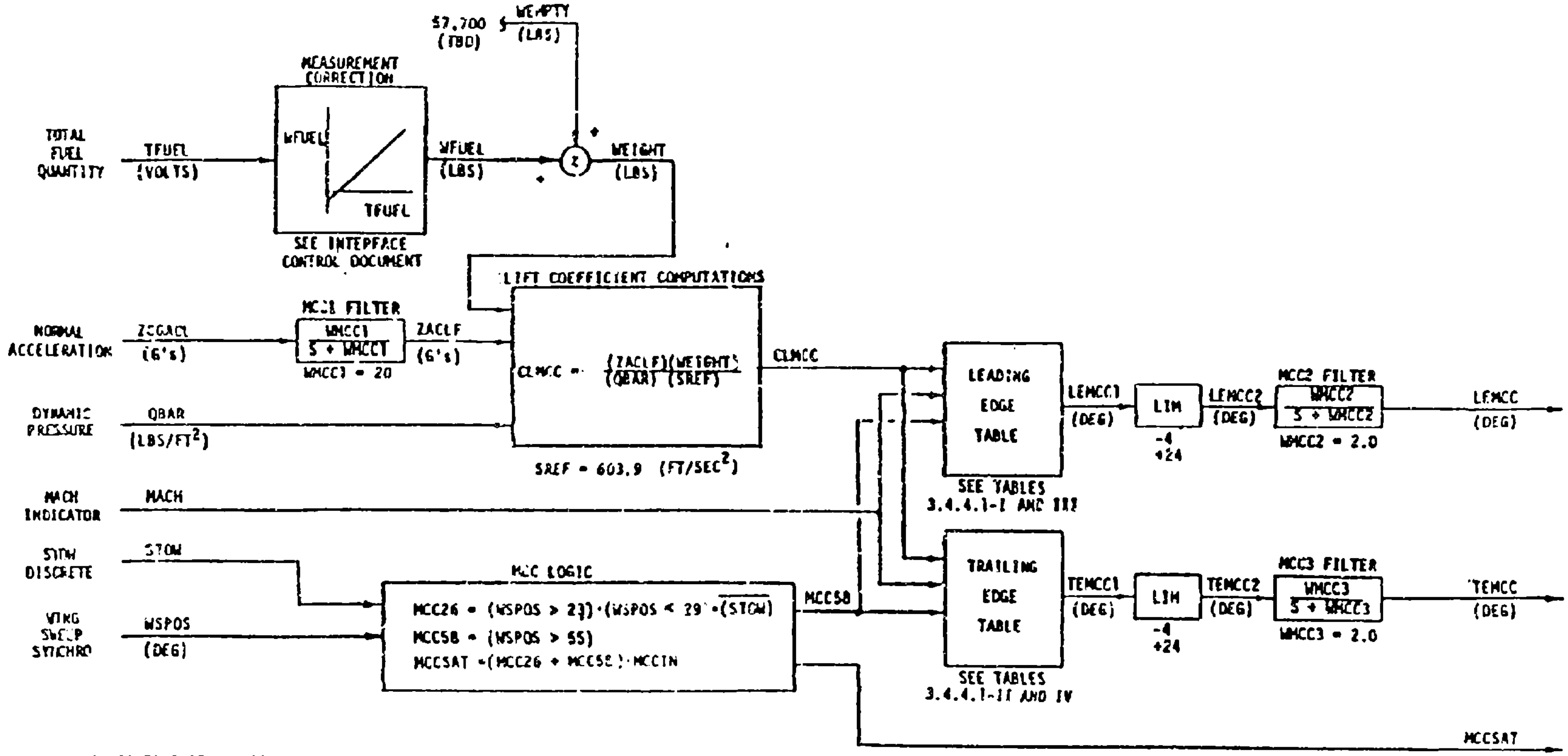
# Increased Aerodynamic Efficiency (AFTI/Tact)




5

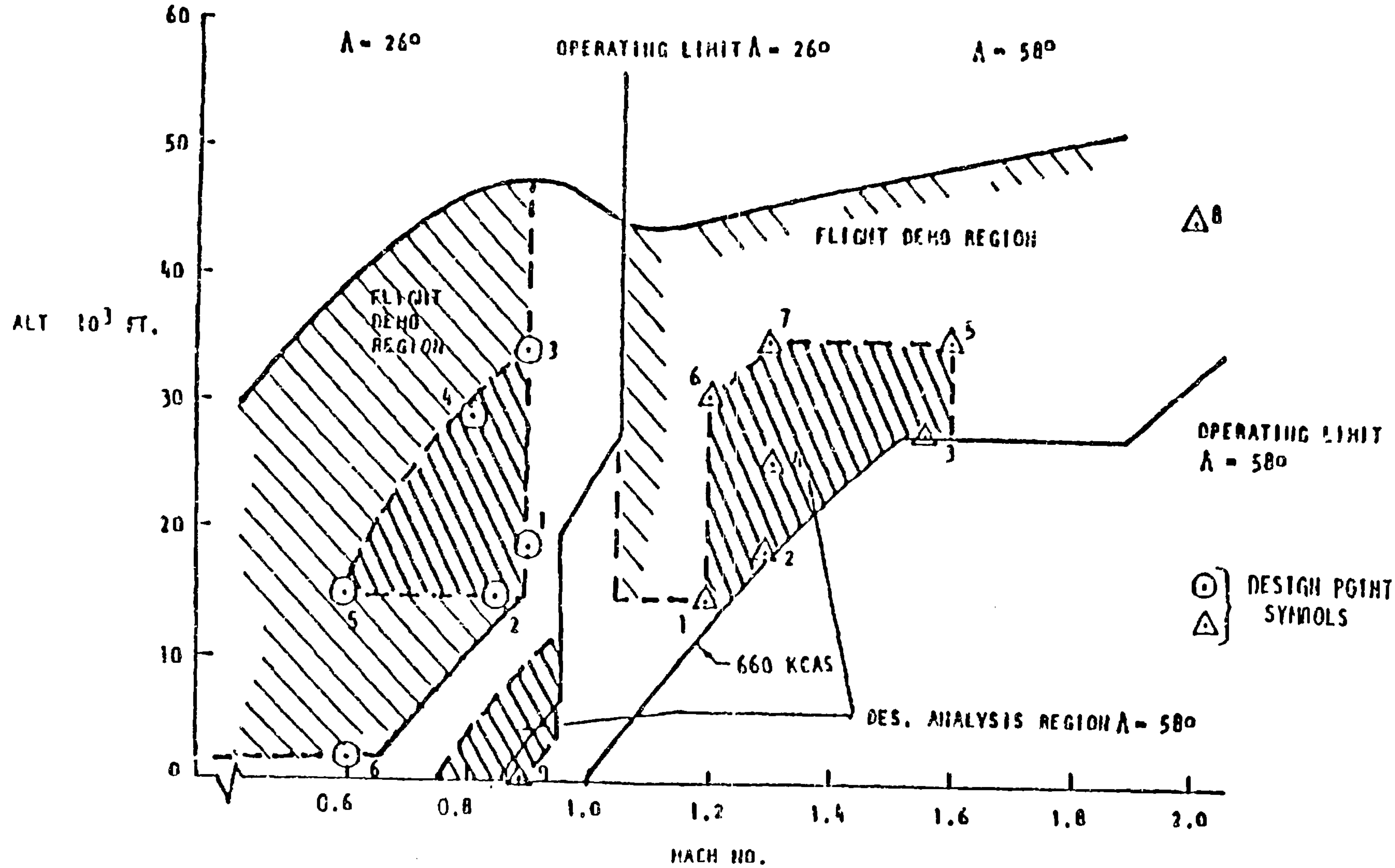



MANEUVER CAMBER CONTROL SYSTEM




MCCIN IS TRUE IF THE FAILURE DETECTION SYSTEM HAS NOT DECLARED A FAILURE IN ANY OF THE FOLLOWING INPUT SIGNALS: TFUEL, ZCGACL, QBAR, MACH, STOW AND WSPOS.

MANEUVER CAMBER CONTROL SYSTEM




MCC DESIGN ENVELOPE/FLIGHT DEMO REGION

TRAILING EDGE COMMANDS FOR 26 DEGREE WING SWEEP

| | M = 0.0 | M = 0.3 | M = 0.60 | M - 0.70 | M = 0.8 | M - 0.85 | M = 0.90 | M = 0.95 |
|---|---|---|---|---|---|---|---|---|
| CLMCC | TEMCC1 | TEMCC1 | TEMCC1 | TEMCC1 | TEMCC1 | TEMCC1 | TEMCC1 | TEMCC1 |
| -.4 | -1.0 | -1.0 | -1.1 | -1.2 | -1.1 | -1.5 | -3.2 | -3.2 |
| -.3 | -0.3 | -0.3 | -0.4 | -0.5 | -0.5 | -0.9 | -2.4 | -2.4 |
| -.2 | 0.4 | 0.4 | 0.3 | 0.2 | 0.2 | -0.3 | -1.6 | -1.6 |
| -.1 | 1.0 | 1.0 | 1.0 | 0.9 | 0.8 | 0.4 | -0.8 | -0.8 |
| 0. | 1.7 | 1.7 | 1.7 | 1.6 | 1.4 | 1.0 | 0.0 | 0.0 |
| .1 | 2.4 | 2.4 | 2.4 | 2.2 | 2.0 | 1.6 | 0.6 | 0.8 |
| .2 | 3.1 | 3.1 | 3.0 | 2.8 | 2.6 | 2.2 | 1.6 | 1.6 |
| .3 | 3.8 | 3.6 | 3.7 | 3.5 | 3.2 | 2.8 | 2.4 | 2.4 |
| .4 | 4.4 | 4.4 | 4.4 | 4.2 | 3.8 | 3.5 | 3.3 | 3.3 |
| .5 | 5.1 | 5.1 | 5.1 | 4.8 | 4.4 | 4.2 | 4.1 | 4.1 |
| .6 | 5.8 | 5.8 | 5.8 | 5.5 | 5.0 | 4.8 | 4.8 | 4.8 |
| .7 | 6.5 | 6.5 | 6.5 | 6.2 | 5.6 | 5.4 | 5.6 | 5.6 |
| .8 | 7.2 | 7.2 | 7.2 | 6.9 | 6.2 | 6.1 | 5.4 | 5.4 |
| .9 | 7.8 | 7.8 | 7.9 | 7.6 | 6.8 | 7.0 | 7.3 | 7.3 |
| 1.0 | 8.6 | 6.6 | 8.7 | 8.3 | 7.5 | 8.4 | 8.3 | 8.3 |
| 1.1 | 10.2 | 10.2 | 10.7 | 9.0 | 8.2 | 10.3 | 9.5 | 9.5 |
| 1.2 | 12.8 | 12.8 | 15.0 | 12.2 | 10.1 | 12.5 | 11.6 | 11.6 |
| 1.3 | 15.4 | 15.4 | 18.2 | 16.6 | 13.5 | 14.7 | 18.0 | 18.0 |
| 1.4 | 18.2 | 18.2 | 20.3 | 19.3 | 16.6 | 17.6 | 18.0 | 18.0 |
| 1.5 | 20.7 | 20.7 | 22.0 | 21.0 | 19.6 | 21.6 | 18.0 | 18.0 |

LEADING EDGE COMMANDS FOR 26 DEGREE WING SWEEP

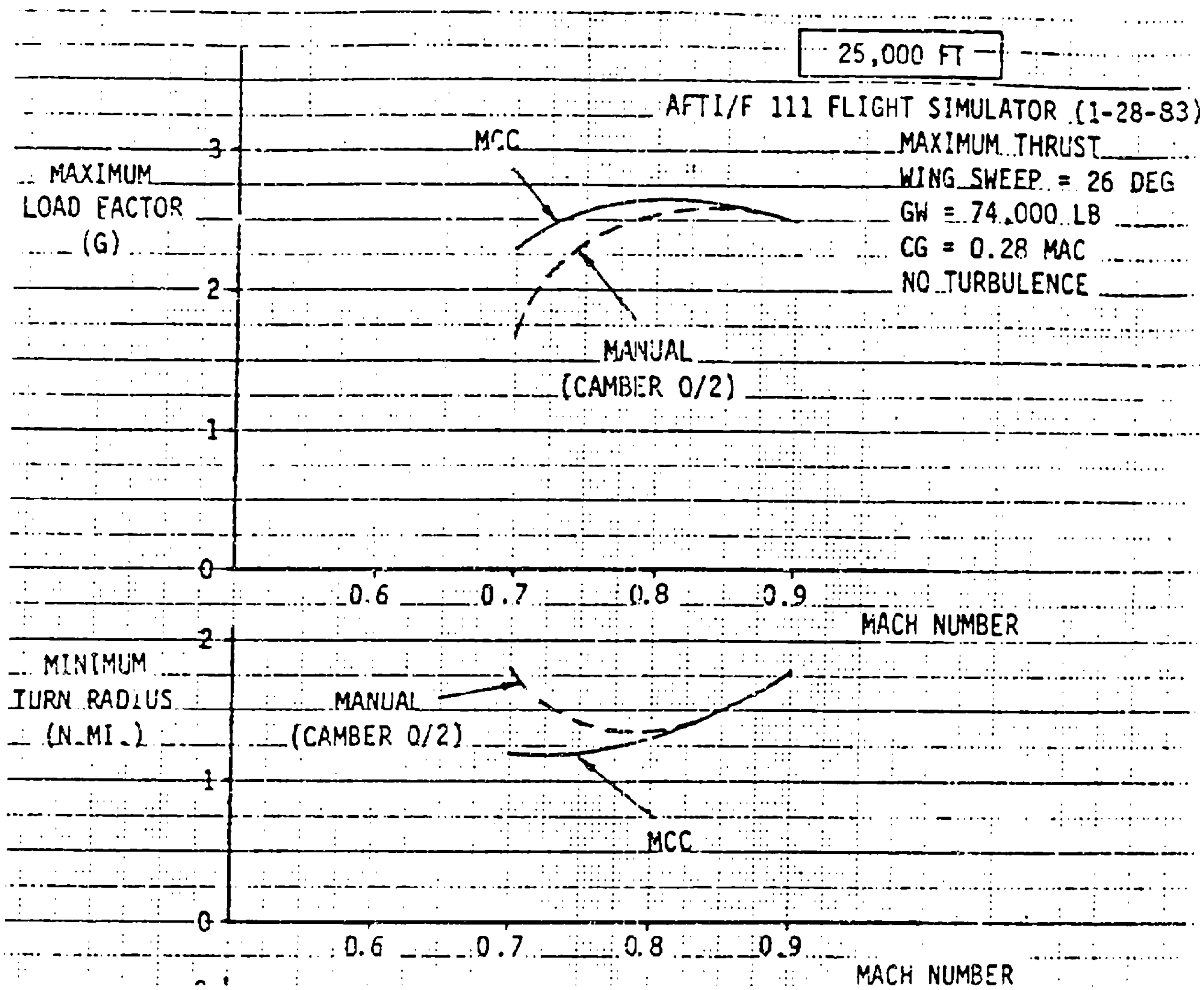
| | M = 0. | M = 0.30 | M = 0.6 | M = 0.70 | M = 0.8 | M = 0.85 | M = .875 | M = 0.9 | M = 0.95 |
|---|---|---|---|---|---|---|---|---|---|
| CLMCC | LEMCC1 | LEMCC1 | LEMCC1 | LEMCC1 | LEMCC1 | LEMCC1 | LEMCC1 | LEMCC1 | LEMCC1 |
| -.4 | -2.5 | -2.5 | -2.4 | -2.4 | -2.3 | -2.3 | -2.2 | -2.2 | -2.2 |
| -.3 | -2.0 | -2.0 | -2.0 | -2.0 | -2.0 | -2.0 | -2.0 | -2.0 | -2.0 |
| -.2 | -1.4 | -1.4 | -1.5 | -1.6 | -1.6 | -1.6 | -1.7 | -1.8 | -1.8 |
| -.1 | -0.8 | -0.8 | -1.0 | -1.1 | -1.3 | -1.3 | -1.4 | -1.5 | -1.5 |
| 0.0 | -0.2 | -0.2 | -0.4 | -0.5 | -0.7 | -1.0 | -1.3 | -1.3 | -1.3 |
| .1 | 0.4 | 0.4 | 0.2 | 0.1 | -0.4 | -0.8 | -1.0 | -1.1 | -1.1 |
| .2 | 1.2 | 1.2 | 0.9 | 0.7 | 0.0 | -0.4 | -0.7 | -0.8 | -0.8 |
| .3 | 1.9 | 1.9 | 1.4 | 1.1 | 0.4 | 0.0 | 0.0 | -0.6 | -0.6 |
| .4 | 2.7 | 2.7 | 2.0 | 1.6 | 0.9 | 0.4 | 0.0 | -0.4 | -0.4 |
| .5 | 3.5 | 3.5 | 2.7 | 2.3 | 1.4 | 0.8 | 0.3 | -0.1 | -0.1 |
| .6 | 4.5 | 4.5 | 3.4 | 2.9 | 2.0 | 1.3 | 0.7 | 0.2 | 0.2 |
| .7 | 5.5 | 5.5 | 4.2 | 3.6 | 2.6 | 1.7 | 1.2 | 0.5 | 0.5 |
| .8 | 6.7 | 6.7 | 5.0 | 4.3 | 3.2 | 2.3 | 1.6 | 0.8 | 0.8 |
| .9 | 8.2 | 8.2 | 5.8 | 5.1 | 3.8 | 2.9 | 2.2 | 1.2 | 1.2 |
| 1.0 | 9.7 | 9.7 | 6.7 | 5.8 | 4.6 | 3.6 | 2.7 | 1.6 | 1.6 |
| 1.1 | 12.2 | 12.2 | 7.7 | 6.7 | 5.5 | 4.4 | 3.4 | 2.2 | 2.2 |
| 1.2 | 16.0 | 16.0 | 9.0 | 7.7 | 6.5 | 5.4 | 4.4 | 2.9 | 2.9 |
| 1.3 | 22.0 | 22.0 | 10.4 | 6.7 | 7.7 | 7.0 | 6.3 | 4.2 | 4.2 |
| 1.4 | 22.0 | 22.0 | 12.4 | 10.9 | 10.2 | 10.0 | 10.0 | 10.0 | 10.0 |
| 1.5 | 22.0 | 22.0 | 16.2 | 15.3 | 14.7 | 15.0 | 18.0 | 22.0 | 22.0 |
| 1.6 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 | 22.0 |

LEADING EDGE COMMANDS FOR 58 DEGREE WING SWEEP

| | M = 0.94 | M = 1.0 | M = 1.5 | M = 2.0 | M = 2.5 |
|---|---|---|---|---|---|
| CLMCC | LEMCC1 | LEMCC1 | LEMCC1 | LEMCC1 | LEMCC1 |
| -.4 | -1.1 | -1.1 | -1.1 | -1.1 | -1.1 |
| -.3 | -1.1 | -.9 | -1.1 | -1.1 | -1.1 |
| -.2 | -1.1 | -.1 | -1.1 | -1.1 | -1.1 |
| 0. | -1.1 | 0.5 | -.8 | -1.1 | -.9 |
| .1 | -.5 | 1.3 | -.2 | -.9 | .6 |
| .2 | 1.4 | 2.5 | .9 | .2 | 2.9 |
| .3 | 3.2 | 4.4 | 2.5 | 2.3 | 6.3 |
| .4 | 5.0 | 7.6 | 5.2 | 5.5 | 12.2 |
| .5 | 6.8 | 16.3 | 10.0 | 12.4 | 20.6 |
| .6 | 8.6 | 20.6 | 20.6 | 20.6 | 20.6 |
| .7 | 10.4 | 20.6 | 20.6 | 20.6 | 20.6 |
| .8 | 12.2 | 20.6 | 20.6 | 20.6 | 20.6 |
| .9 | 14.0 | 20.6 | 20.6 | 20.6 | 20.6 |
| 1.0 | 15.8 | 20.6 | 20.6 | 20.6 | 20.6 |
| 1.1 | 17.4 | 20.6 | 20.6 | 20.6 | 20.6 |
| 1.2 | 17.4 | 20.6 | 20.6 | 20.6 | 20.6 |

## TRAILING EDGE COMMANDS FOR 58 DEGREE WING SWEEP

| | M = 0.94 | M = 1.0—2.5 |
|---|---|---|
| CLMCC | TEMCC1 | TEMCC1 |
| -.4 | -.7 | 7.0 |
| -.3 | -.7 | 7.0 |
| -.2 | -.7 | 6.6 |
| -.1 | -.3 | 5.7 |
| 0 | .7 | 4.6 |
| .1 | 1.7 | 3.4 |
| .2 | 2.7 | 1.7 |
| .3 | 3.7 | -.5 |
| .4 | 4.7 | -.7 |
| .5 | 5.7 | -.7 |
| .6 | 6.7 | -.7 |
| .7 | 7.7 | -.7 |
| .8 | 8.7 | -.7 |
| .9 | 9.7 | -.7 |
| 1.0 | 10.7 | -.7 |
| 1.1 | 11.7 | -.7 |
| 1.2 | 12.7 | -.7 |




EFFECT OF MCC MODE ON MAXIMUM SUSTAINABLE LEVEL FLIGHT TURN 25,000 FT.

# MANEUVER LOAD CONTROL (MLC) MODE DEVELOPMENT

George E. Lewis
Boeing Advanced Systems

# Maneuver Load Control System (MLC) Ojectives

- AUTOMATICALLY COMMAND TRAILING EDGE FLAP POSITION TO SHIFT THE WING CENTER OF PRESSURE INBOARD, MAINTAINING WING ROOT BENDING MOMENT AT A LIMIT LEVEL WHILE CONTINUING TO INCREASE AIRPLANE "G" LEVEL

- AIRCRAFT SURFACES NOT USED FOR MLC WILL CONTINUE TO RESPOND TO PILOT INPUTS WHEN MLC IS IN OPERATION

- AIRCRAFT WILL RESPOND IN NORMAL MANNER TO OTHER ENABLED MODES AT OPERATING CONDITIONS BELOW 95% OF WING ROOT BENDING LIMIT

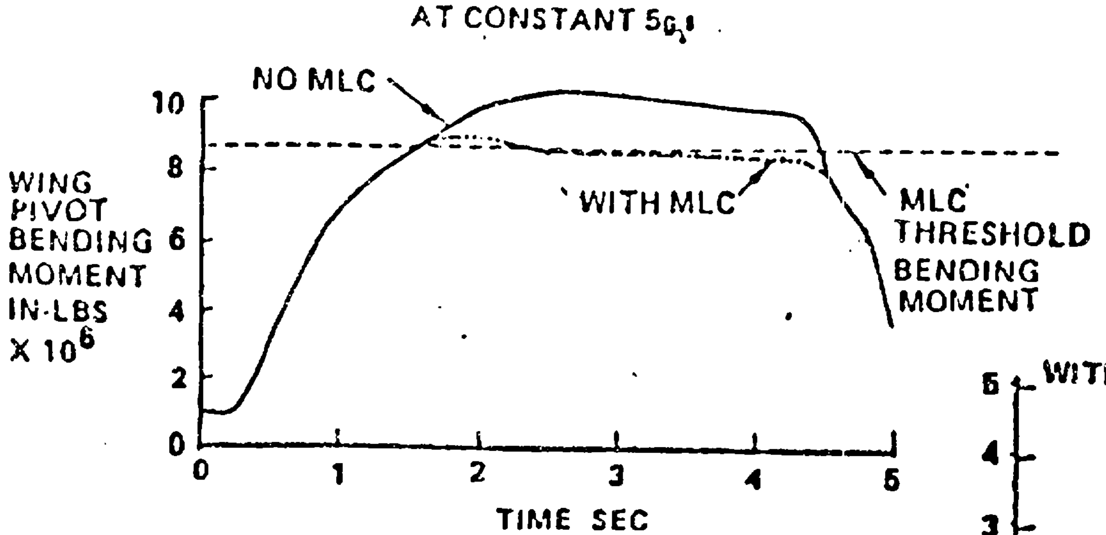
# Maneuver Load Control Approach

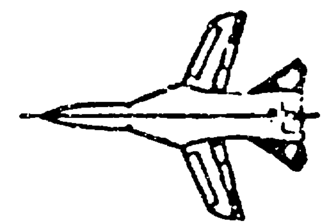
- COMPUTE WING CRITICAL BENDING MOMENT VALUE FOR EACH WING BASED ON ACCELERATIONS, WEIGHT, DYNAMIC PRESSURE, MACH NUMBER, AND LEADING AND TRAILING EDGE POSITIONS.
- COMPARE AGAINST MLC THRESHOLD BENDING MOMENT EQUAL TO 95% OF ALLOWABLE BENDING MOMENT.
- IF COMPUTED BENDING MOMENT EXCEEDS THRESHOLD, MLC SYSTEM COMMANDS OUTBOARD FLAP UP TO REDISTRIBUTE AIRLOAD.
- AIRCRAFT CONTINUES TO RESPOND NORMALLY TO PILOT COMMANDS, BOTH BEFORE AND DURING MLC OPERATION.

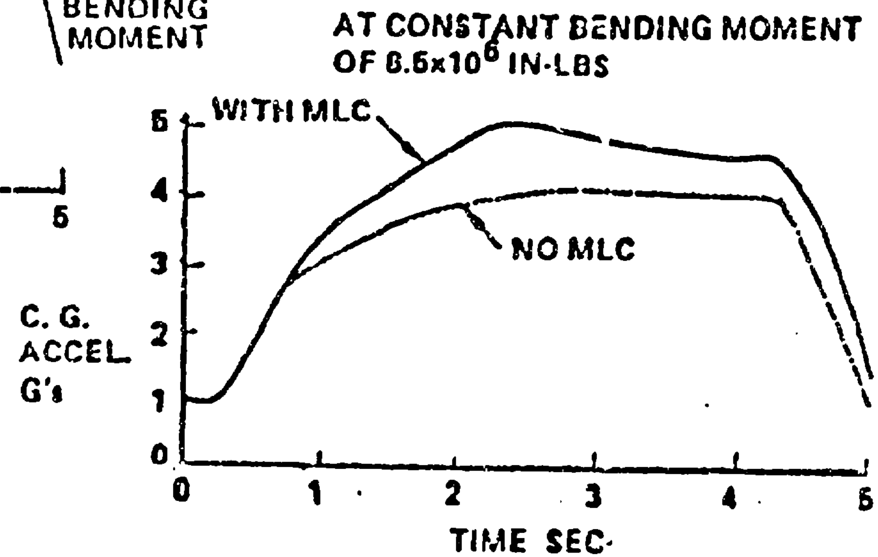
# Maneuver Load Control

Reduce wing root bending moment

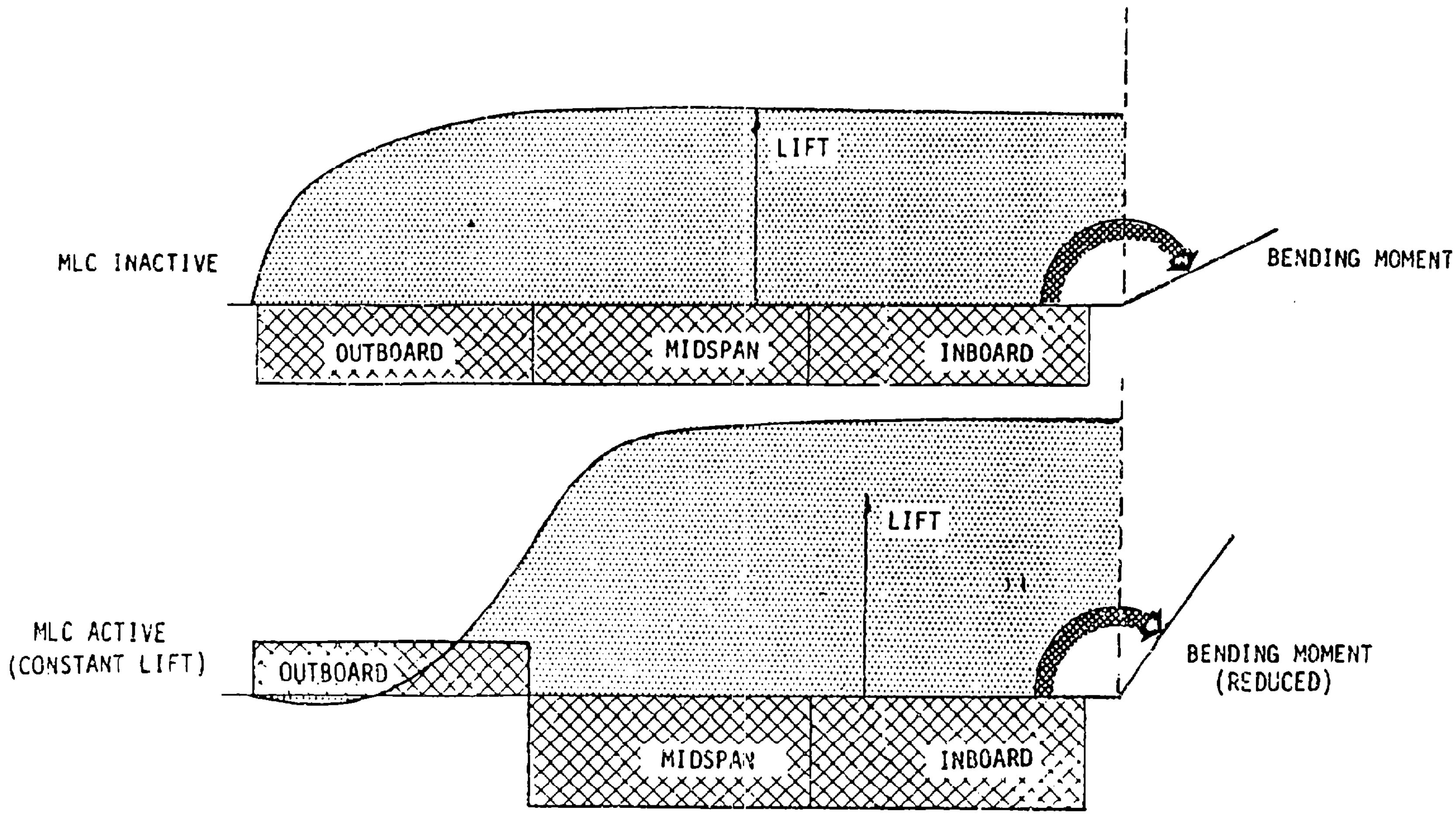
Compare computed bending moment against MLC threshold bending moment, if threshold exceeded MLC commands the outboard flap up to redistribute the airload

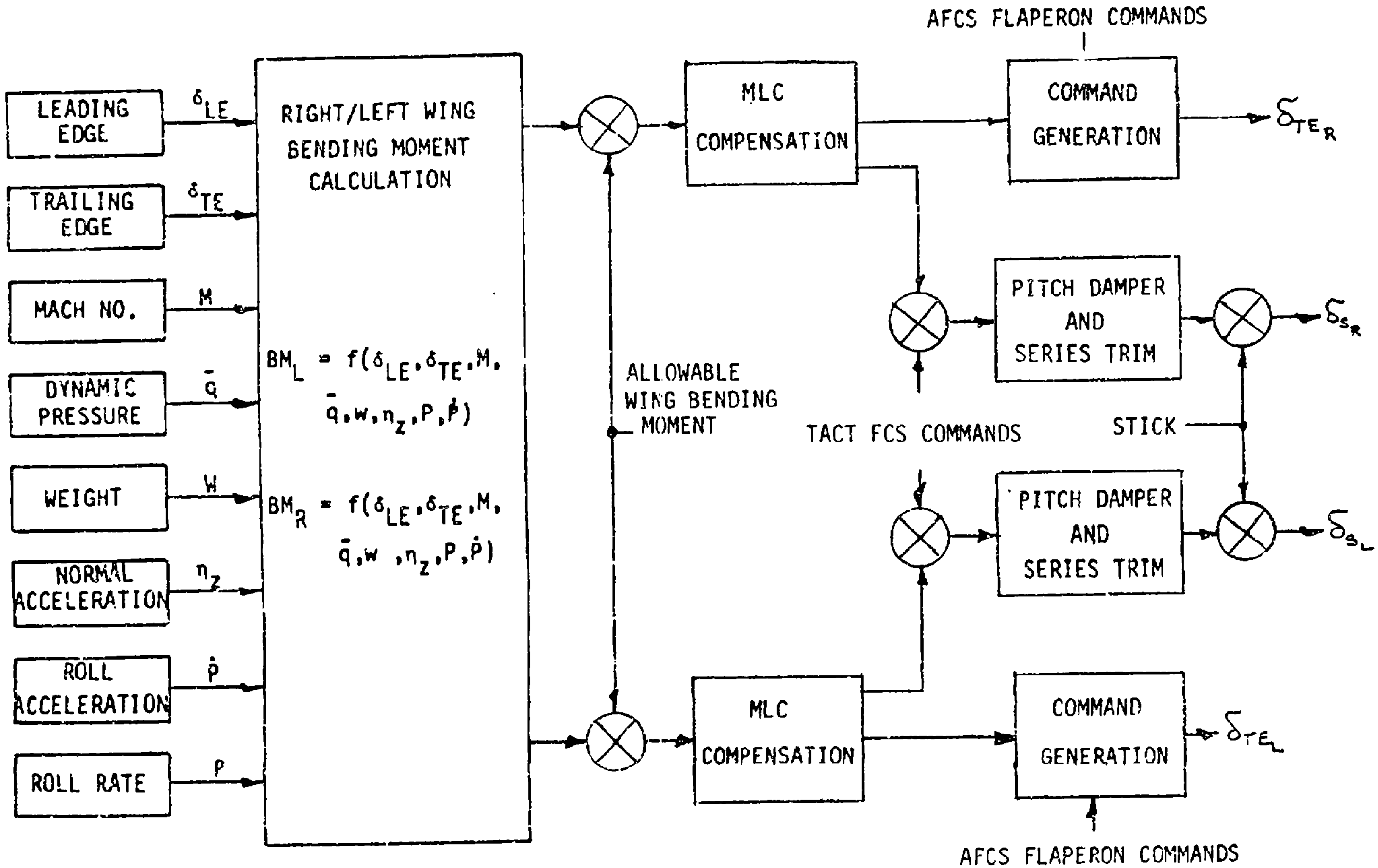




# Effect of MLC on Wing/Body Pressure Distribution

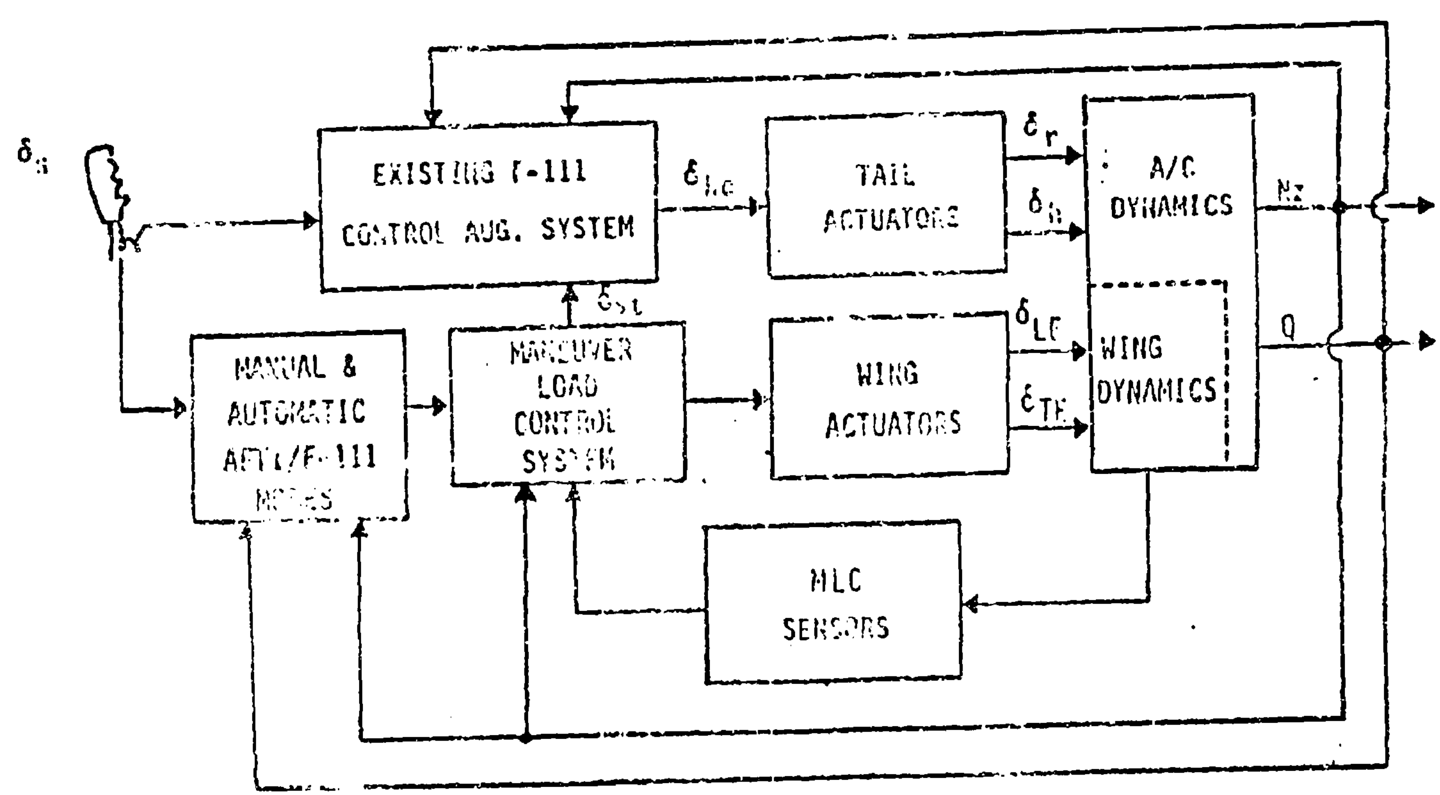




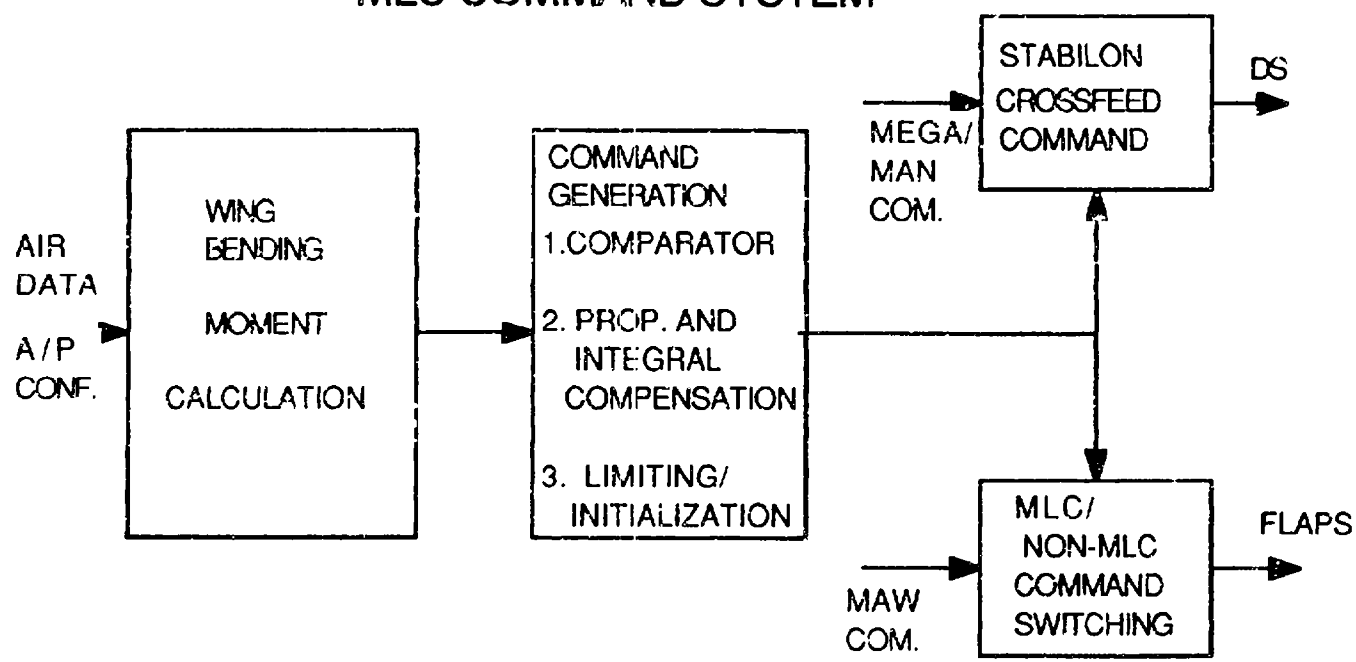

MANEUVER LOAD CONTROLSYSTEM

# AFTI/F-111 Maw Control System Block Diagram

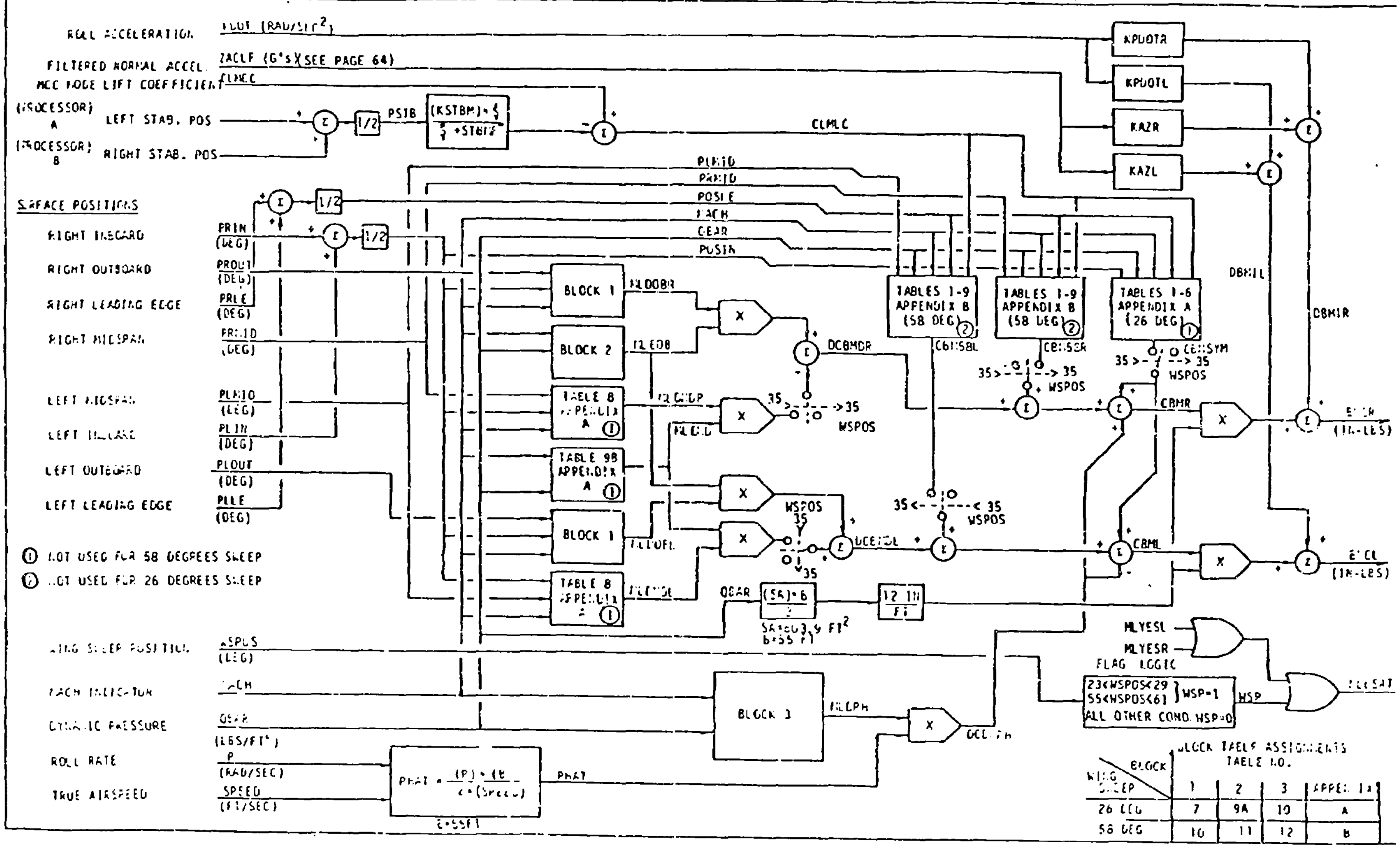
CONTROL SYSTEM DIAGRAM



# MLC COMMAND SYSTEM

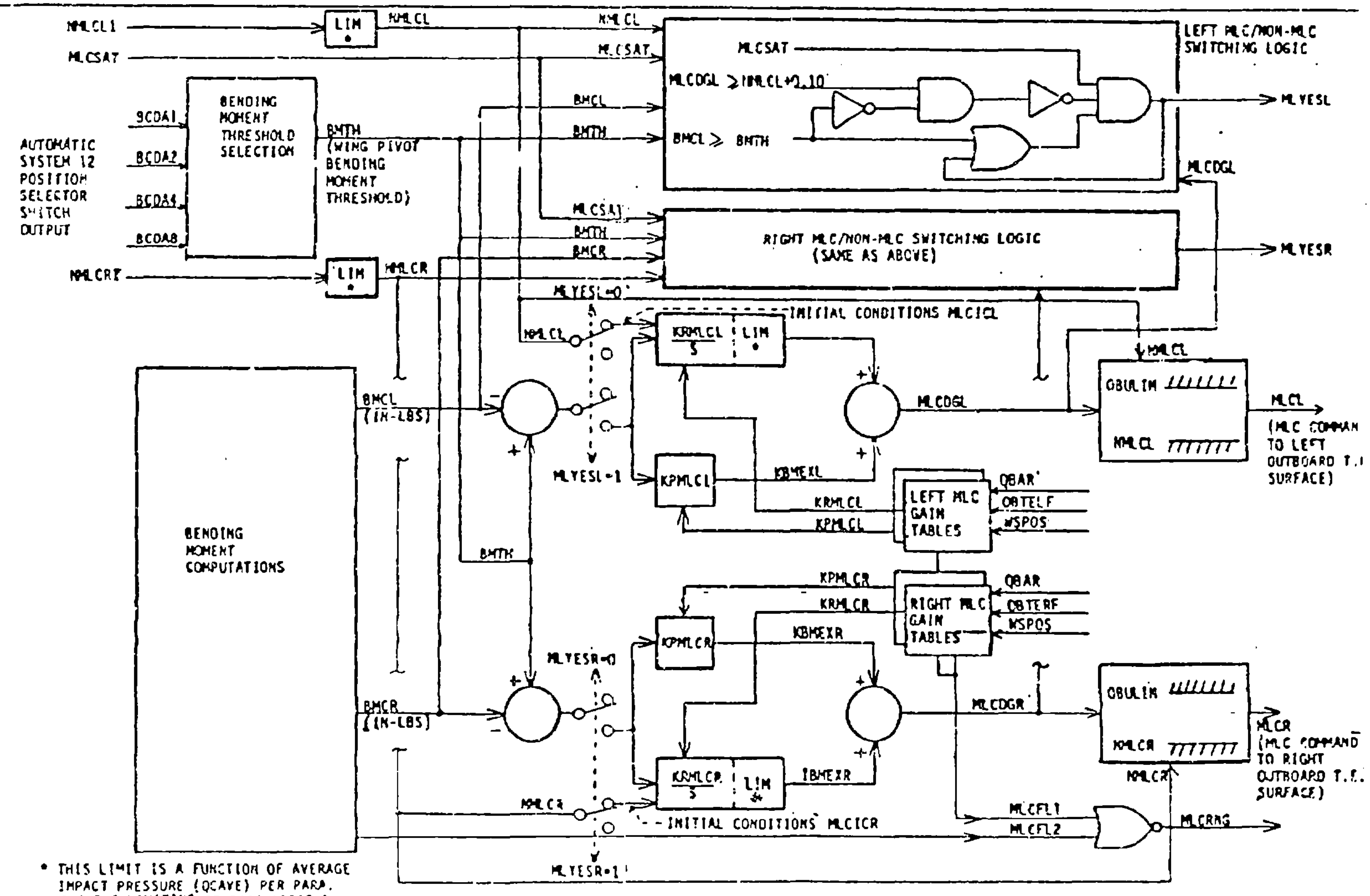


# MLC BENDING MOMENT CALCULATION

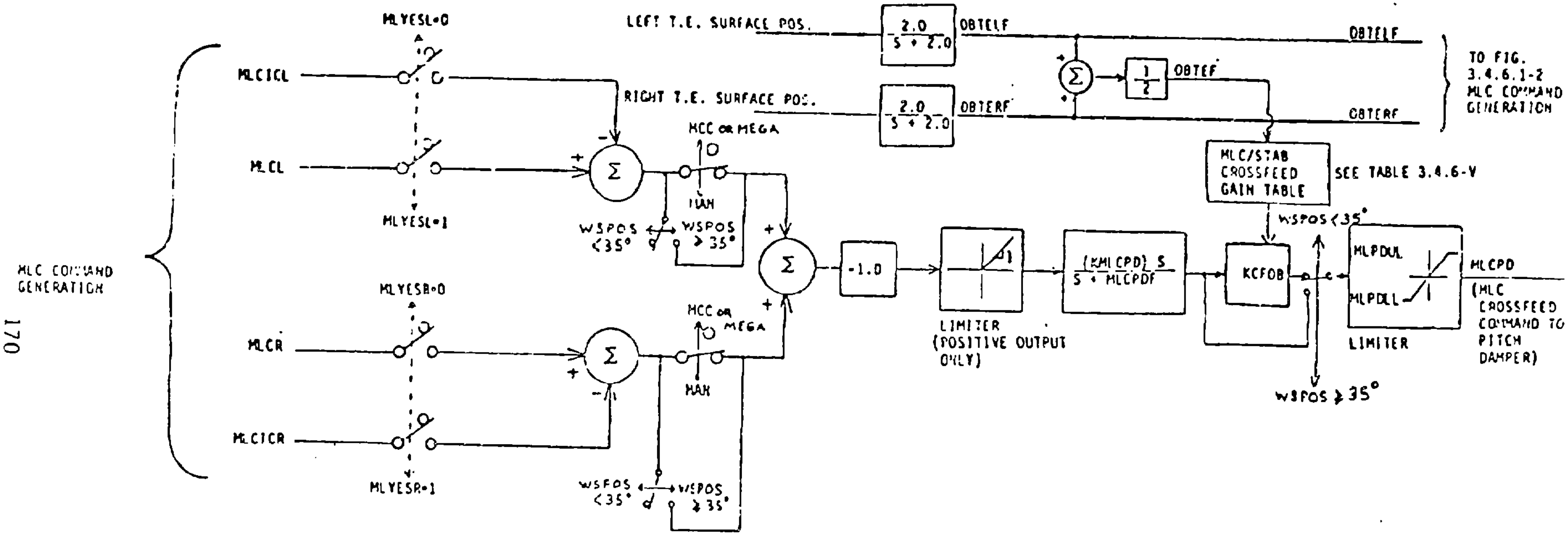



| BLOCK / WING SWEEP | 1 | 2 | 3 | APPENDIX |
|---|---|---|---|---|
| 26 DEG | 7 | 9A | 10 | A |
| 58 DEG | 10 | 11 | 12 | B |

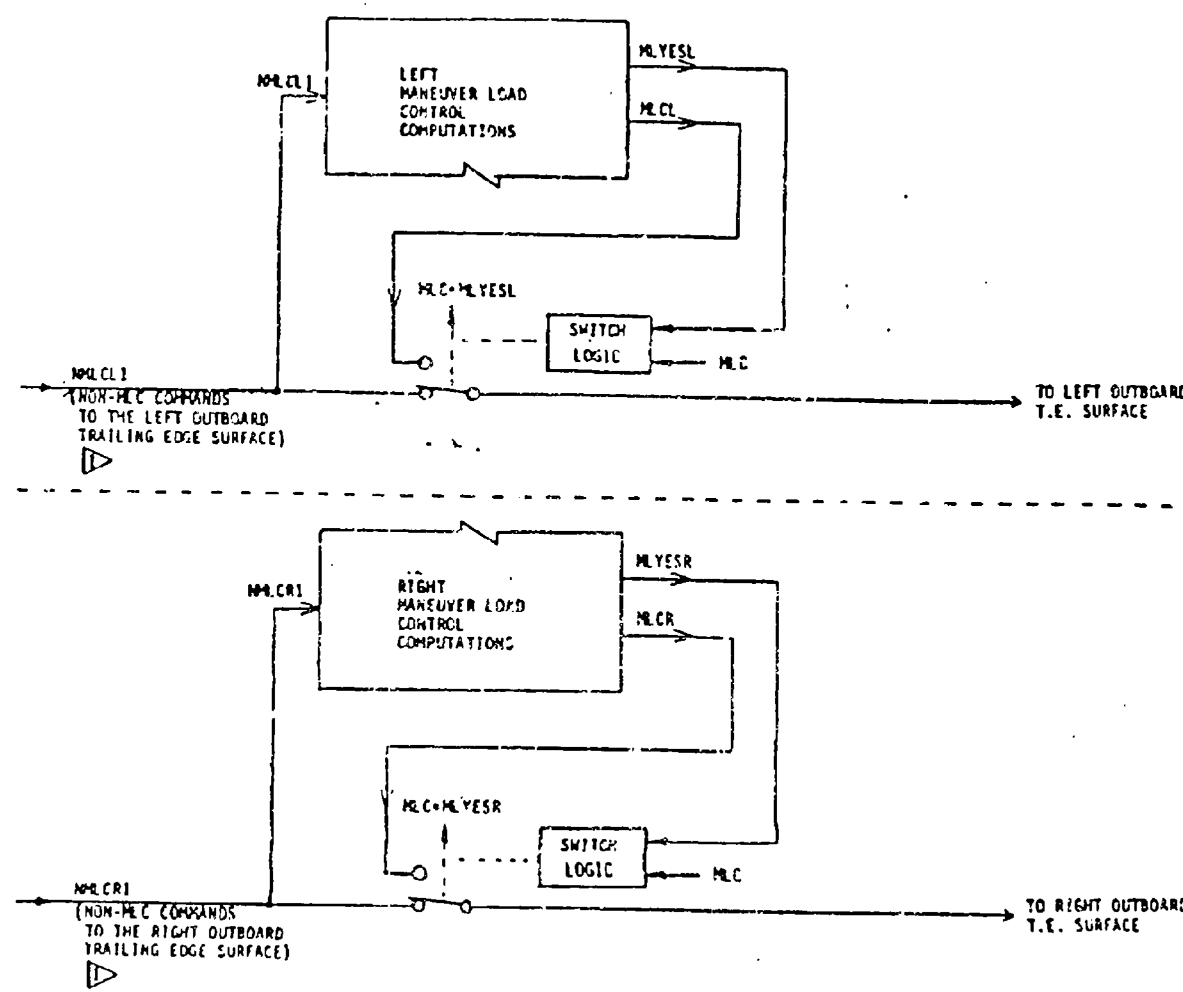
## MLC COMMAND GENERATION



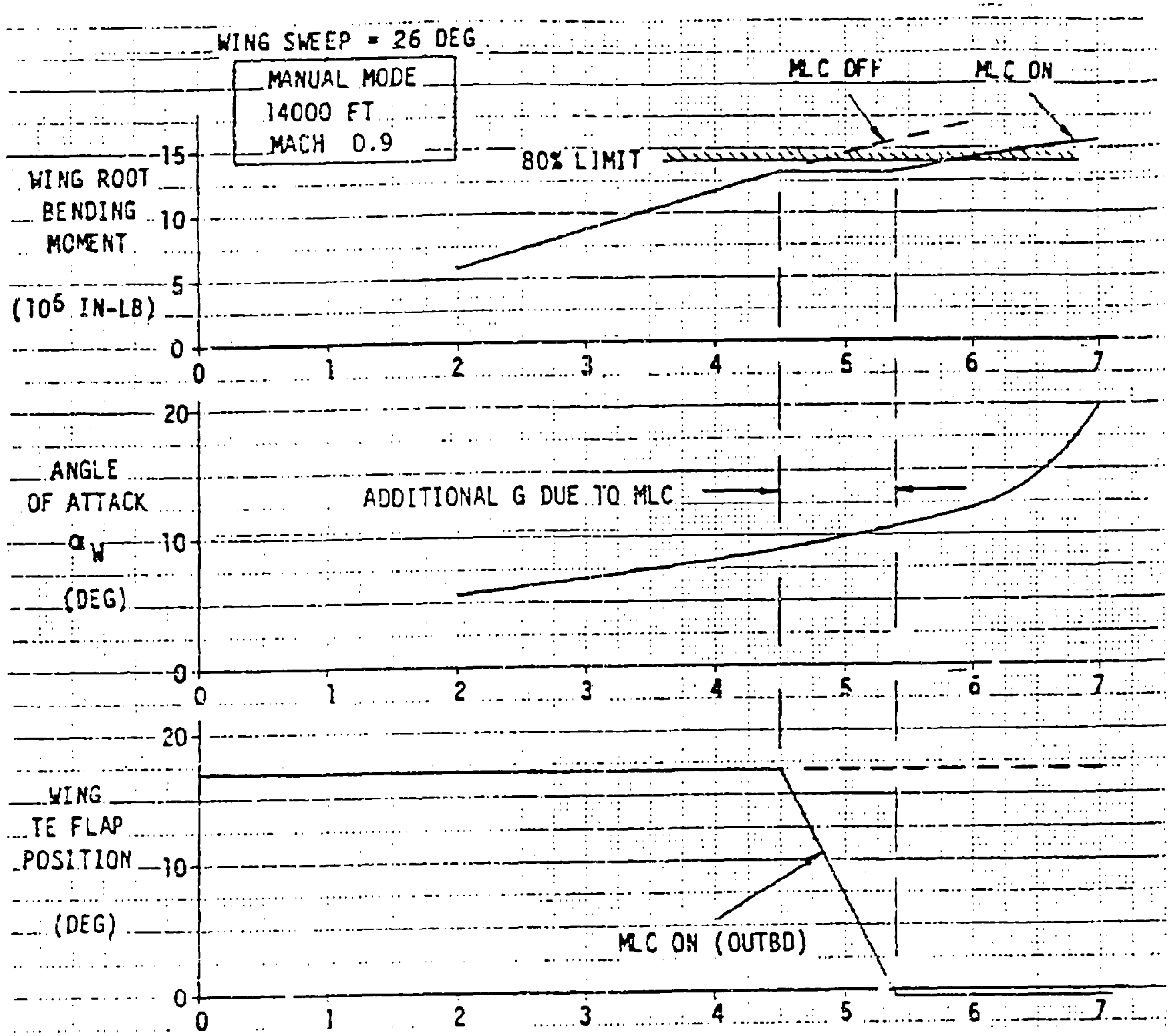

* THIS LIMIT IS A FUNCTION OF AVERAGE IMPACT PRESSURE (QCAVE) PER PARA. 3.3.8.3 LIMITING OF D365-10062-1.



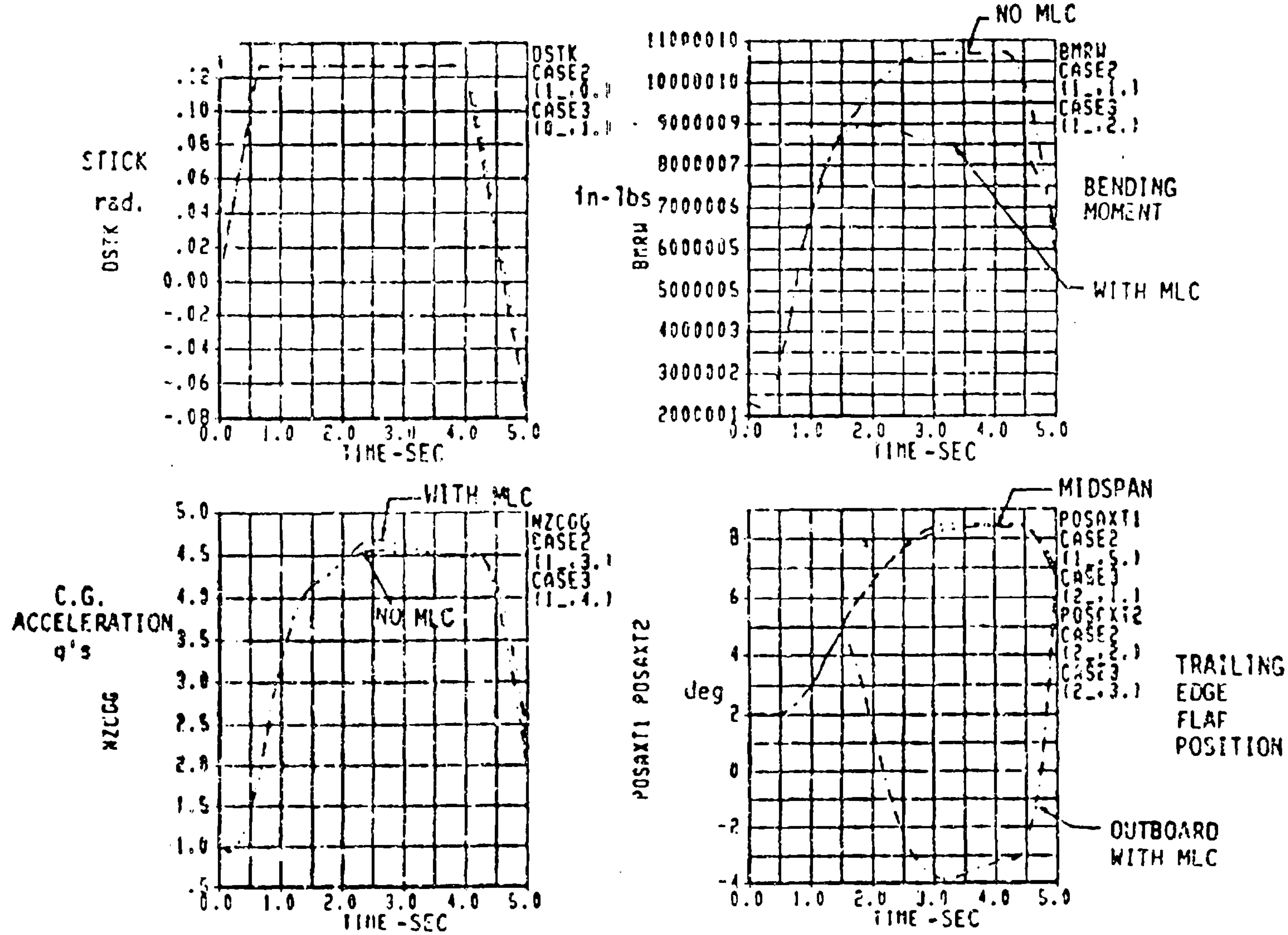

MLC STABILON COMMAND GENERATION




MLC/NON MLC COMMAND SWITCHING




MANEUVER LOAD CONTROL (MLC) PERFORMANCE ON AFTI/F-111 FLIGHT SIMULATOR WITH MANUAL 14,000 FT MACH 0.9 SWEEP 26




AIRPLANE RESPONSES - WING LOAD RELIEF
(NO CROSSFEED TO STABILON)

# MANEUVER ENHANCEMENT/GUST ALLEVIATION (ME/GA) MODE DEVELOPMENT

Daniel C. Norman
Boeing Advanced Systems

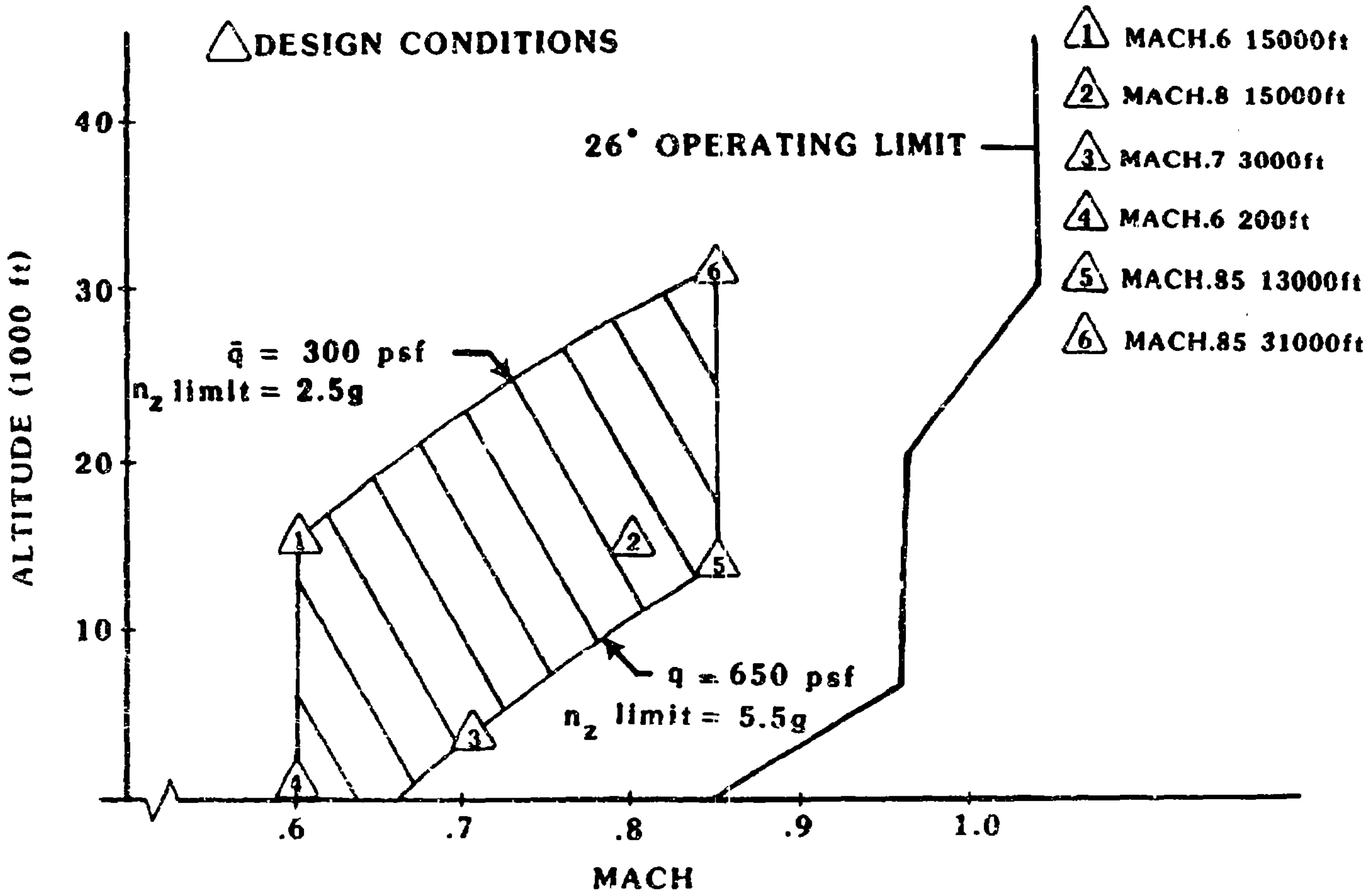
## PERFORMANCE OBJECTIVES

- MANEUVER ENHANCEMENT
  - $n_z$ RESPONSE TIME REDUCED BY 50%
  - ACCEPTABLE ACTUATOR RATES
  - STEADY-STATE WING CAMBER TO MAXIMIZE LIFT/DRAG
  - SMOOTH RESPONSE WITH MINIMAL OVERSHOOT
  - NO DEGRADATION OF GUST RESPONSE

- GUST ALLEVIATION
  - GUST INDUCED RMS G'S REDUCED BY 50%
  - ACCEPTABLE ACTUATOR RATES
  - GOOD STABILITY MARGINS
  - NO DEGRADATION OF COMMAND RESPONSE

- PERFORMANCE EVALUATED BY COMPARING RESPONSE OF ME/GA MODE TO EXISTING COMMAND AUGMENTATION SYSTEM (CAS)

# ME/GA FLIGHT DEMONSTRATION ENVELOPE

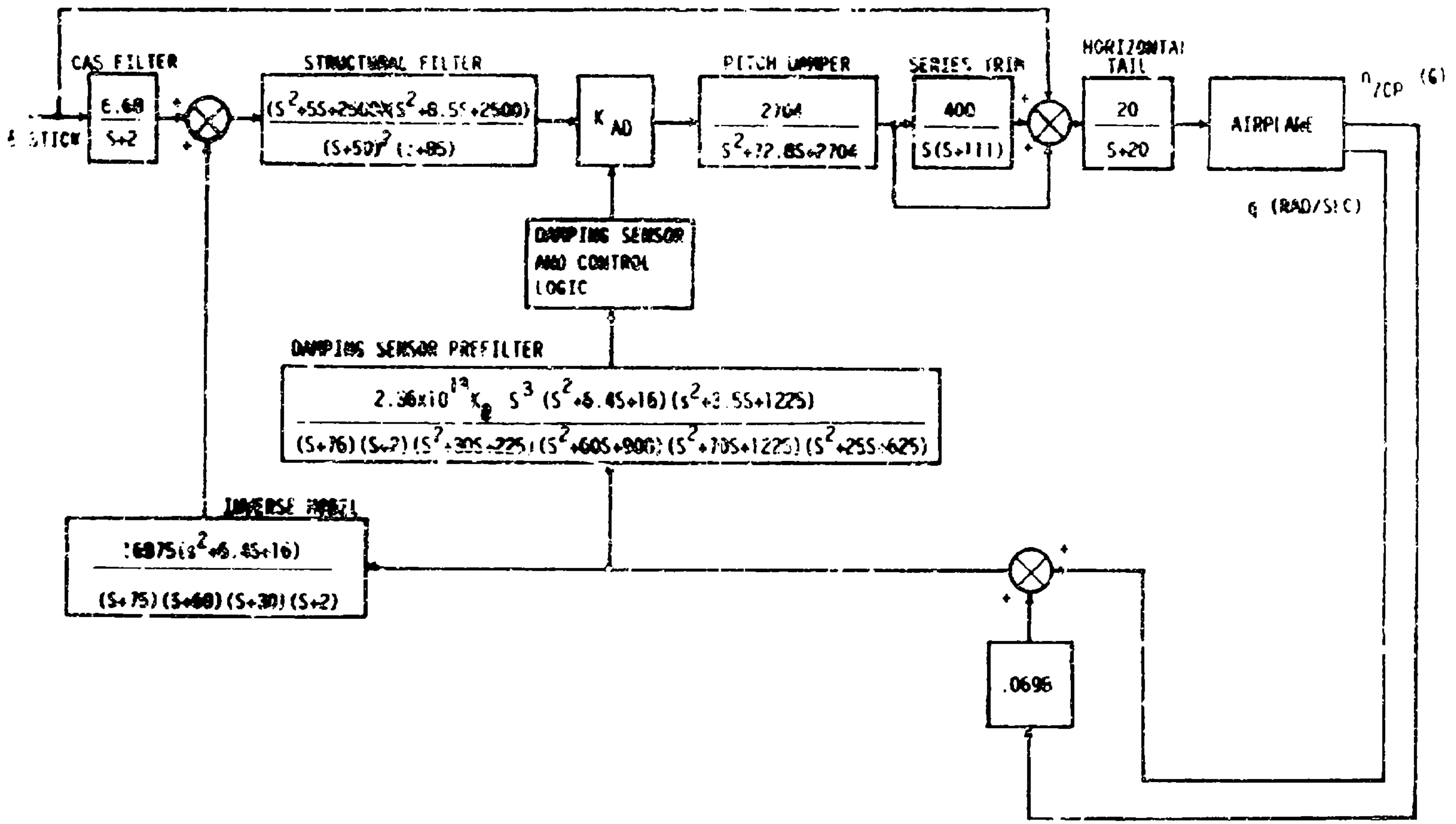


# DESIGN APPROACH

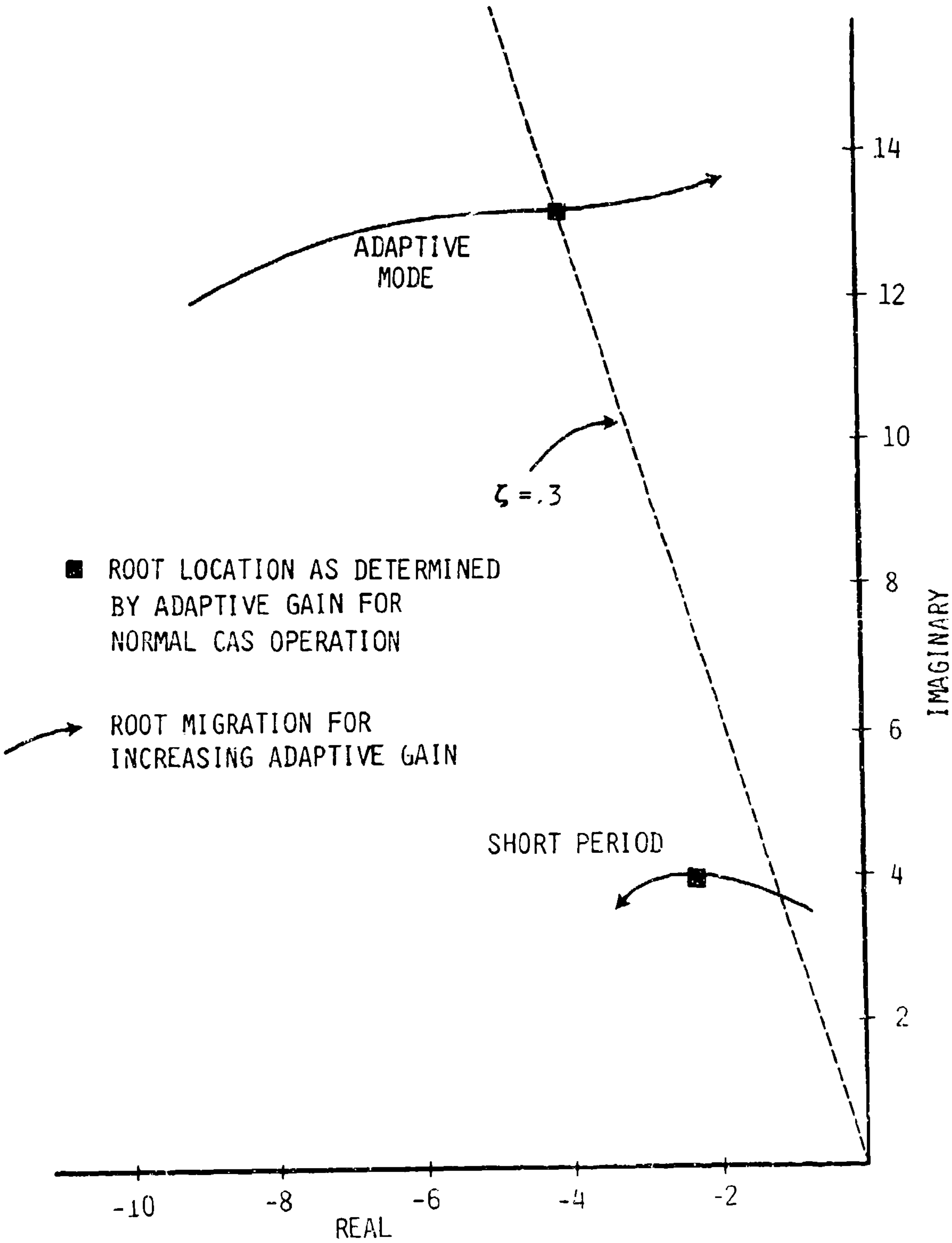
- LINEAR REGULATOR
- EXPLICIT MODEL FOLLOWING
- FREQUENCY SHAPED CRITERIA
- ROBUST KALMAN FILTER
- CONTROLLER REDUCTION VIA MODEL RESIDUALIZATION

# DESIGN PROBLEMS

- Existing Control Loop With Fixed Adaptive Gain
- No Direct Access To Horizontal Tail Actuator
- Strong Adverse Coupling Between Tail and Trailing Edge
- Extremely Nonlinear Wing Characteristics




EXISTING LONGITUDINAL COMMAND AUGMENTATION SYSTEM (CAS)




ROOT LOCUS OF EXISTING CAS
AS A FUNCTION OF ADAPTIVE GAIN

## COUPLING BETWEEN STABILON AND TRAILING EDGE FLAP

- STABILON GENERATES SIGNIFICANT ADVERSE LIFT RELATIVE TO TRAILING EDGE

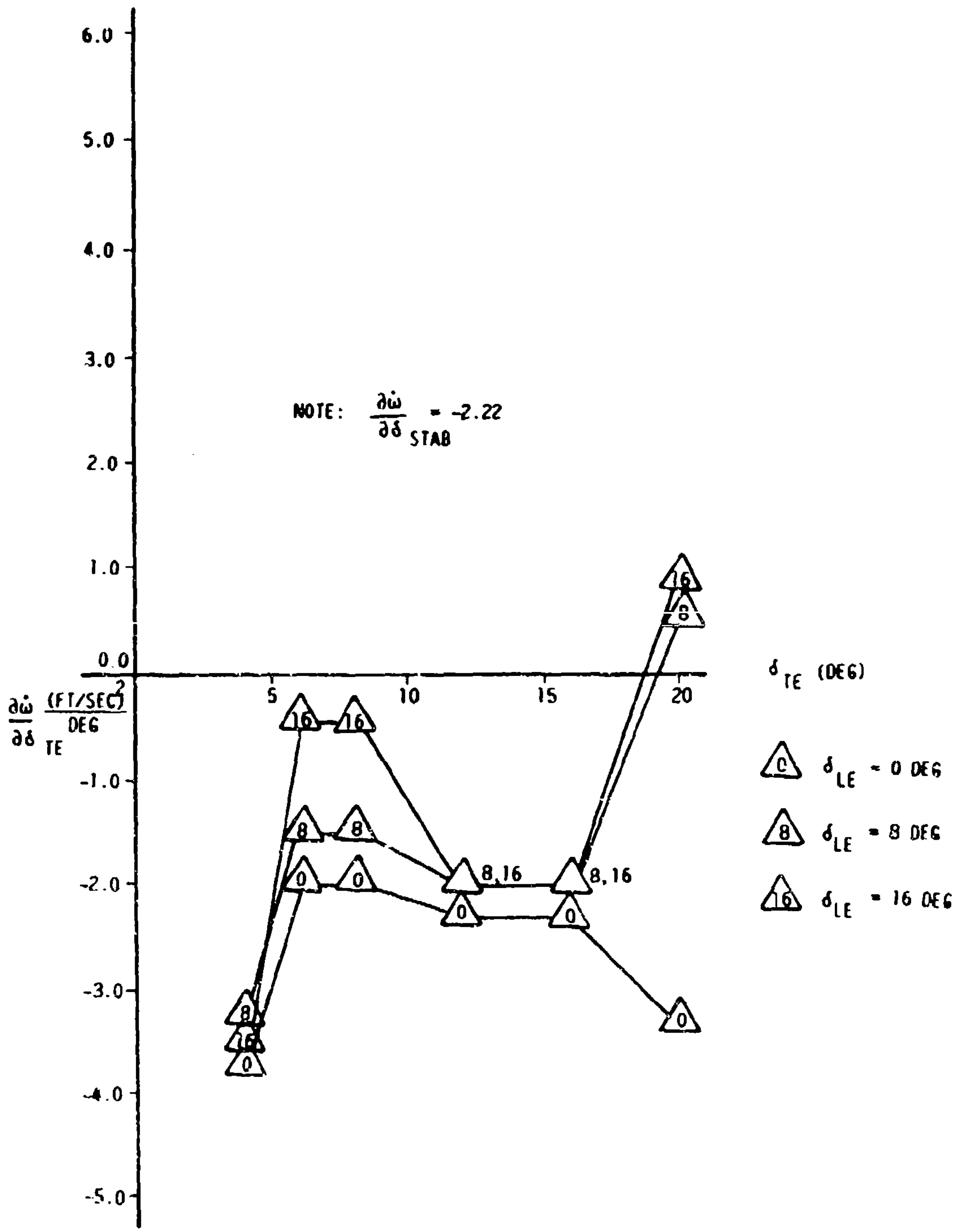
$$\frac{\partial \dot{W} / \partial \delta TE}{\partial \dot{W} / \partial \delta STAB}$$

VARIES FROM 1.3 TO 2.1
AT 1g TRIM CONDITIONS
IN ME/GA DESIGN ENVELOPE

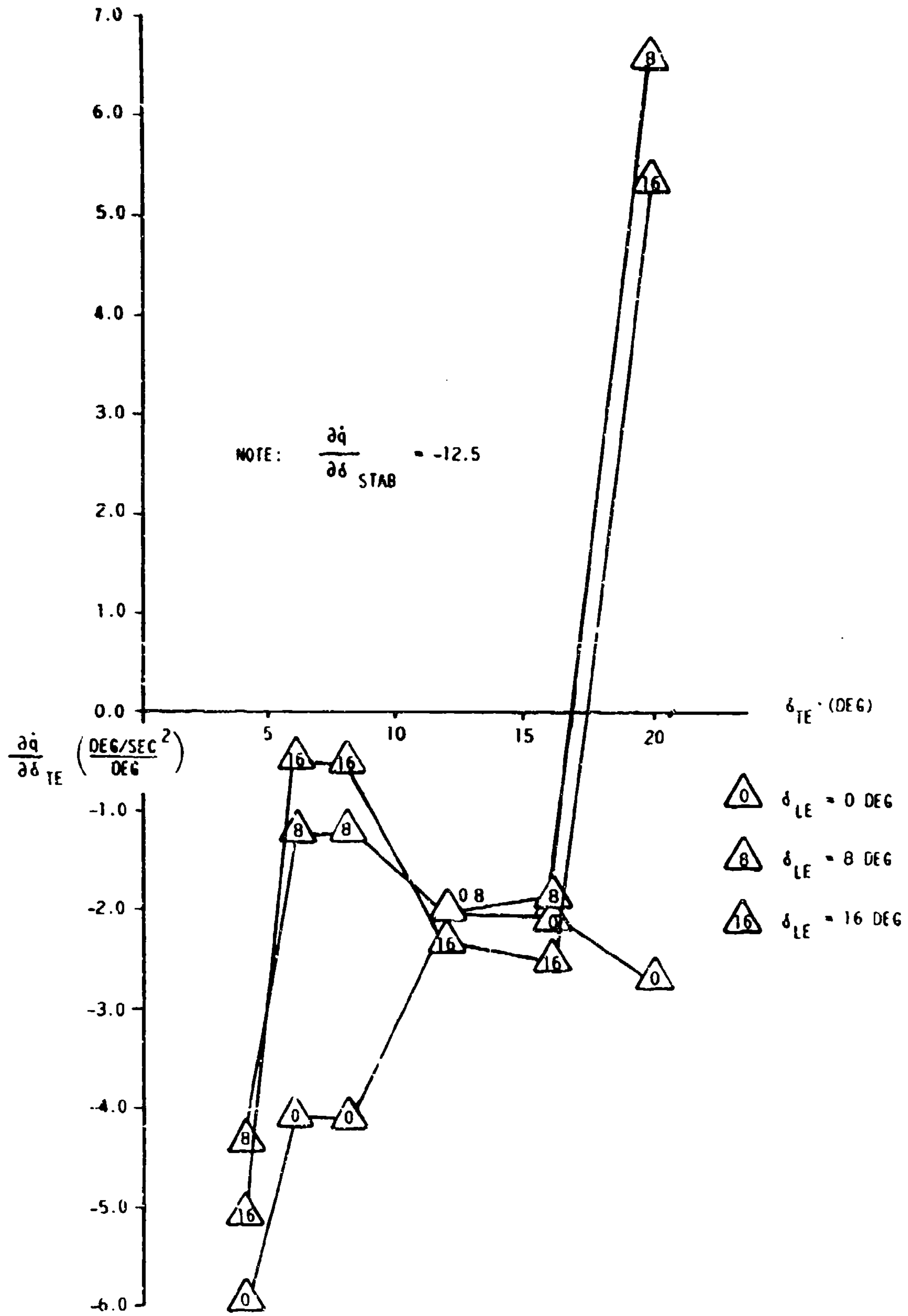
- TRAILING EDGE GENERATES SIGNIFICANT ADVERSE PITCHING MOMENT RELATIVE TO STABILON

$$\frac{\partial \dot{q} / \partial \delta TE}{\partial \dot{q} / \partial \delta STAB}$$

VARIES FROM .47 TO .55
AT 1g TRIM CONDITIONS
IN ME/GA DESIGN ENVELOPE

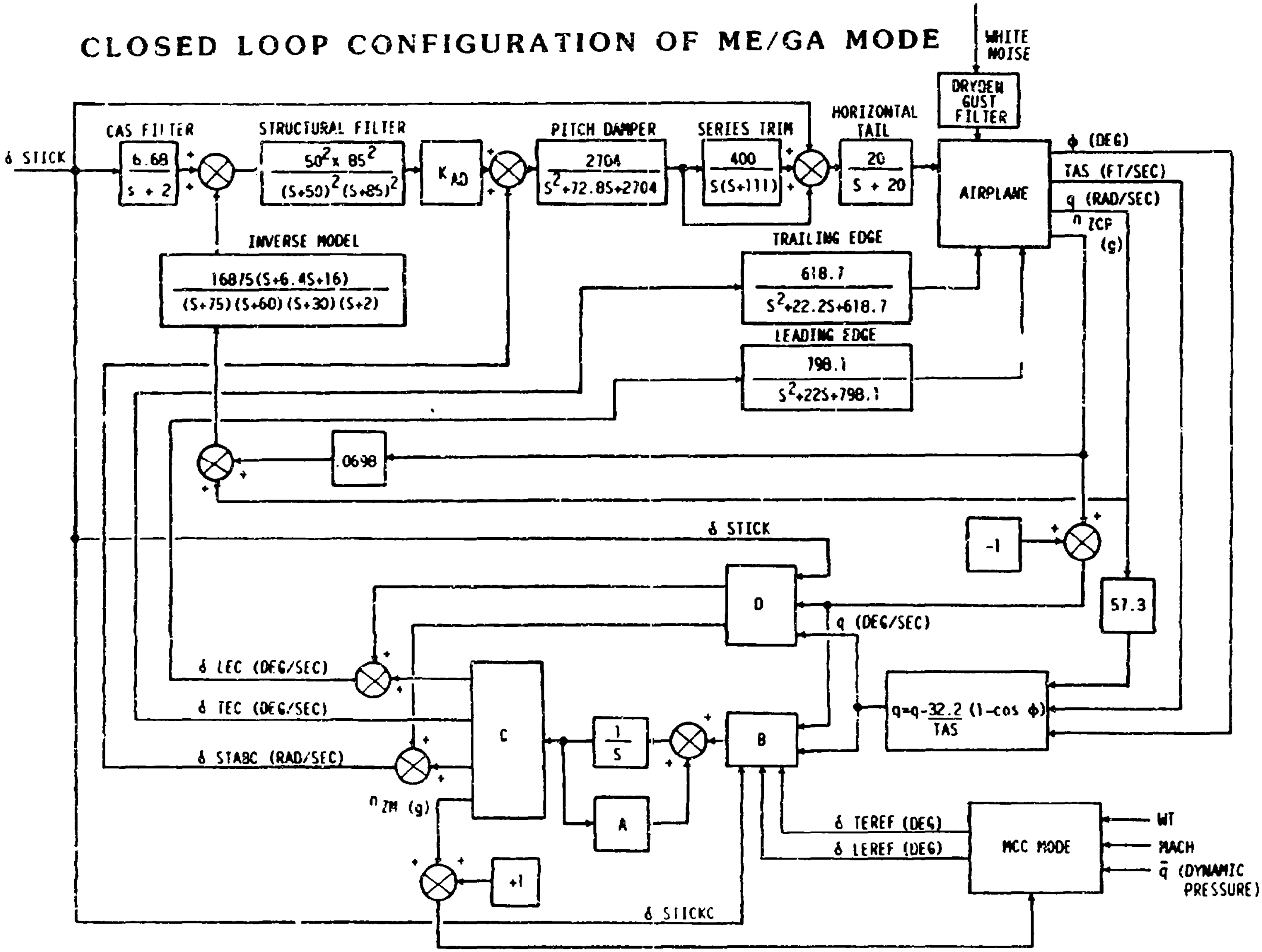



TRAILING EDGE EFFECTIVENESS (VERTICAL ACCELERATION)
AS A FUNCTION OF WING CAMBER, MACH .8, 15000 ft.
1.0g LOAD FACTOR




TRAILING EDGE EFFECTIVENESS (PITCH ACCELERATION) AS A FUNCTION OF WING CAMBER, MACH .8, 15000 ft, 1.0g LOAD FACTOR

# CLOSED LOOP CONFIGURATION OF ME/GA MODE



# PERFORMANCE SUMMARY

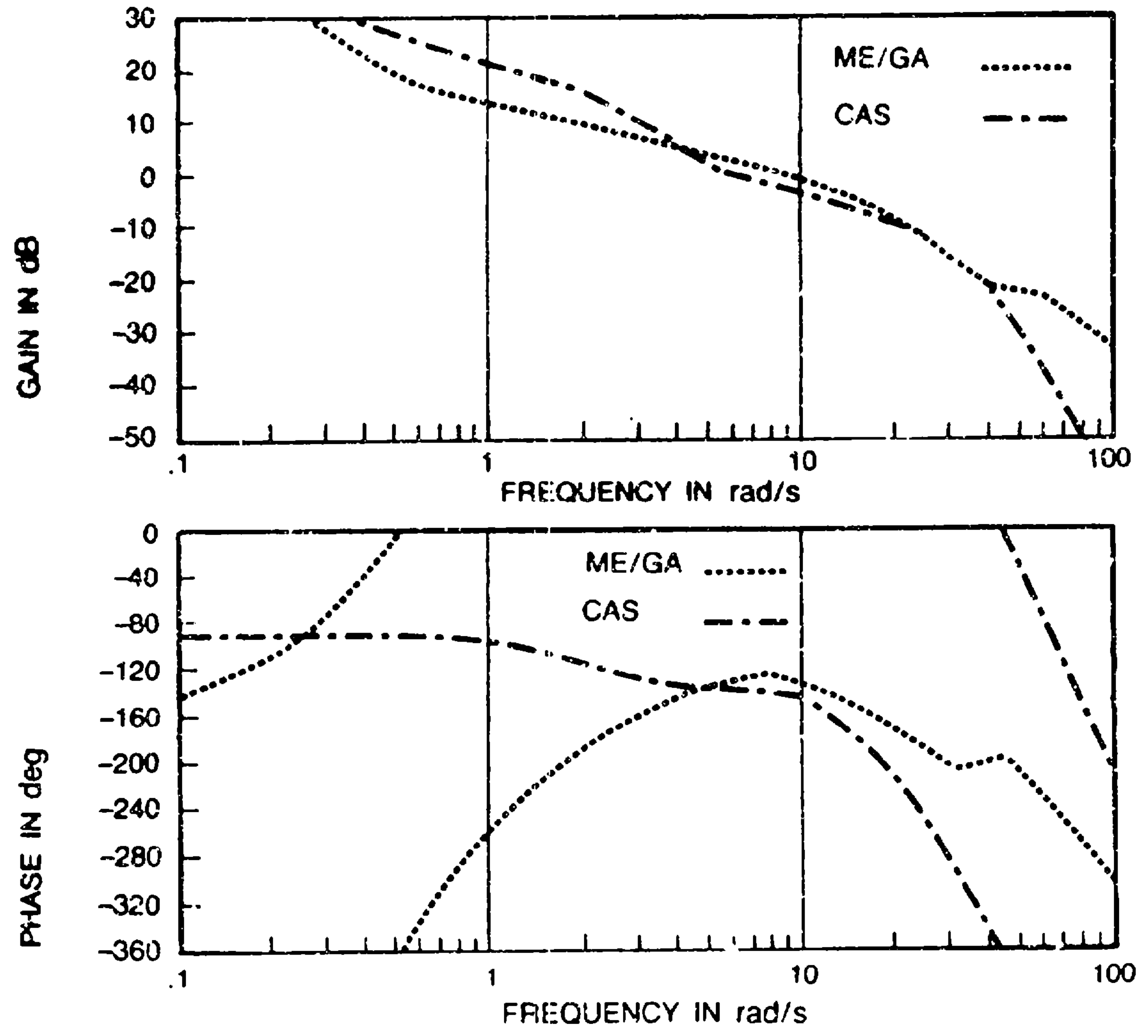
- STABILITY CHARACTERISTICS
- GUST RESPONSE
- COMMAND RESPONSE
- HANDLING QUALITIES

| MODE | | $K_{AD}$ | SHORT PERIOD DAMPING | ADAPTIVE MODE DAMPING |
|---|---|---|---|---|
| EXISTING AUGMENTATION SYSTEM | NORMAL | $.33 \le K_{AD} \le .82$ | $.42 \le \zeta_{SP} \le .60$ | $\zeta_{AM} = .3$ |
| | FIXED GAIN | $K_{AD} = .40$ | $.26 \le \zeta_{SP} \le .45$ | $.20 \le \zeta_{AM} \le .59$ |
| ME/GA | FIXED GAIN | $K_{AD} = .40$ | $.41 \le \zeta_{SP} \le 1.0$ | $.40 \le \zeta_{AM} \le .66$ |

EFFECT OF FIXING ADAPTIVE GAIN. $K_{AD}$, ON DAMPIMG RATIO OF SHORT PERIOD AND ADAPTIVE MODES IN ME/GA DEMONSTATION ENVELOPE

# HORIZONTAL TAIL CONTROL LOOP FREQUENCY RESPONSE

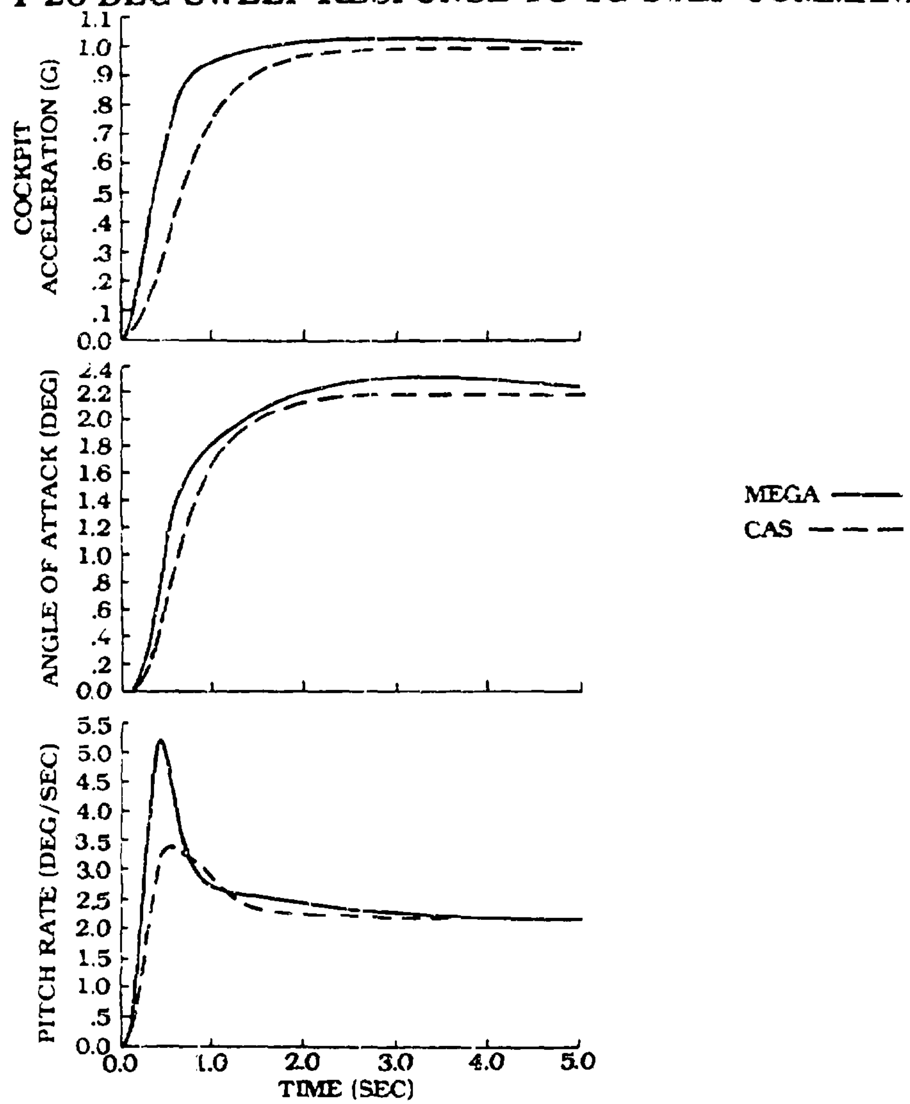
## COMPARISON OF ME/GA MODE AND EXISTING CAS 15 000 ft, MACH .8, 1.0g LOAD FACTOR



BOEING ADVANCED SYSTEMS

# AFTI/F-111 COMMAND RESPONSE

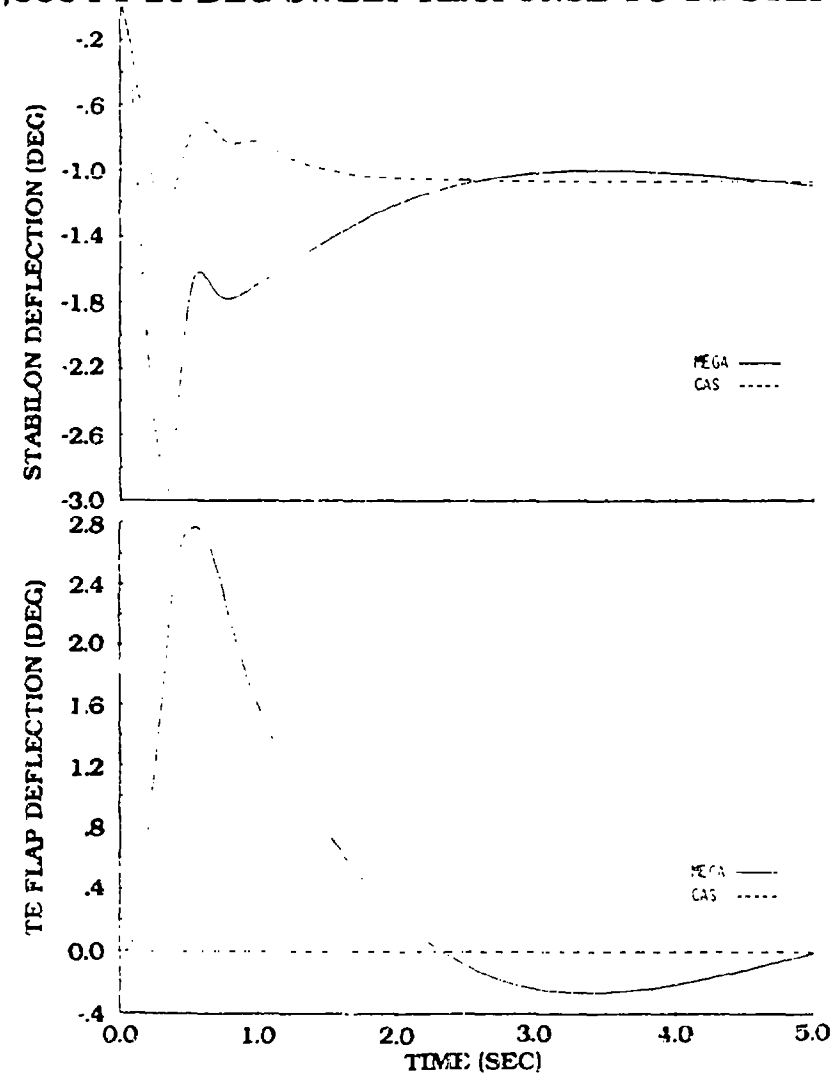
## Mach .8 15,000 FT 26 DEG SWEEP RESPONSE TO 1G STEP COMMAND



BOEING ADVANCED SYSTEMS

# AFTI/F-111 COMMAND RESPONSE

## Mach .8 15,000 FT 26 DEG SWEEP RESPONSE TO 1G STEP COMMAND



| | 1.0 g | 4.0 g |
|---|---|---|
| $\frac{\partial \dot{Q}}{\partial \delta STAB}$ | -11.4 | -11.4 |
| $\frac{\partial \dot{Q}}{\partial \delta TE}$ | -6.29 | +0.11 |

| | | |
|---|---|---|
| $\frac{\partial \dot{W}}{\partial \delta STAB}$ | -2.06 | -2.06 |
| $\frac{\partial \dot{W}}{\partial \delta TE}$ | -4.21 | -2.06 |

EFFECT OF FLOW SEPARATION ON TRAILING EDGE EFFECTIVENESS
AT MACH .6 200 FT

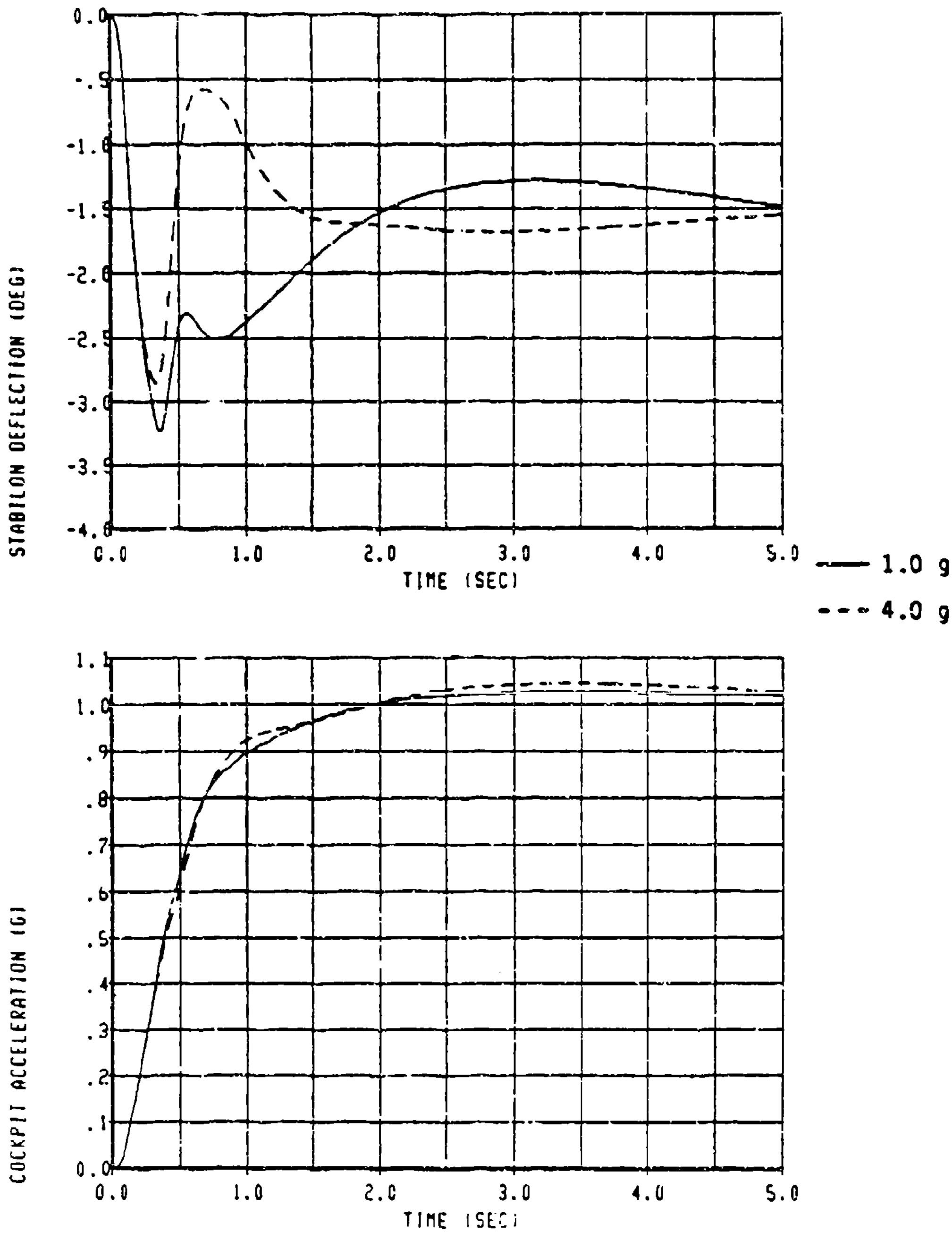
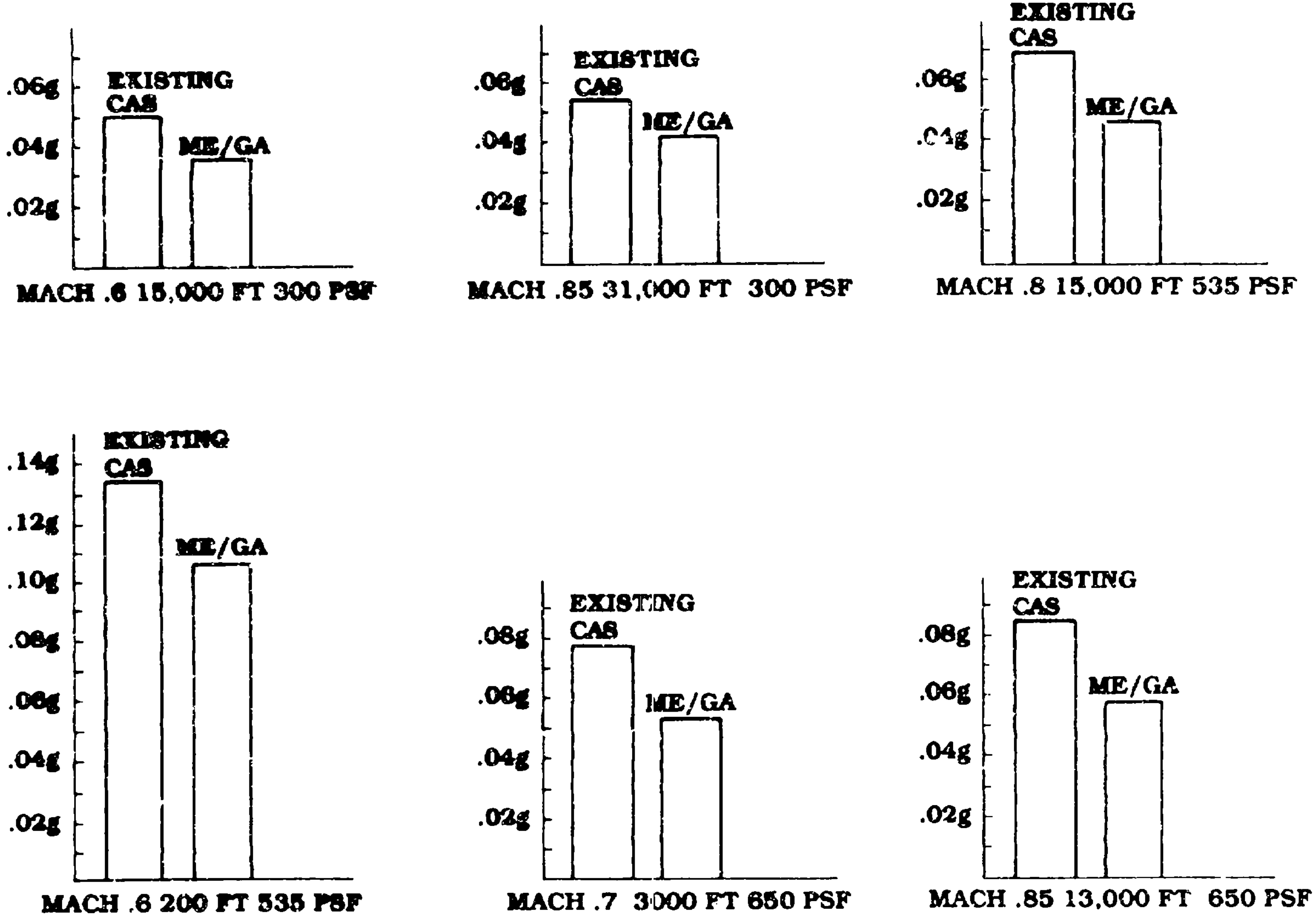


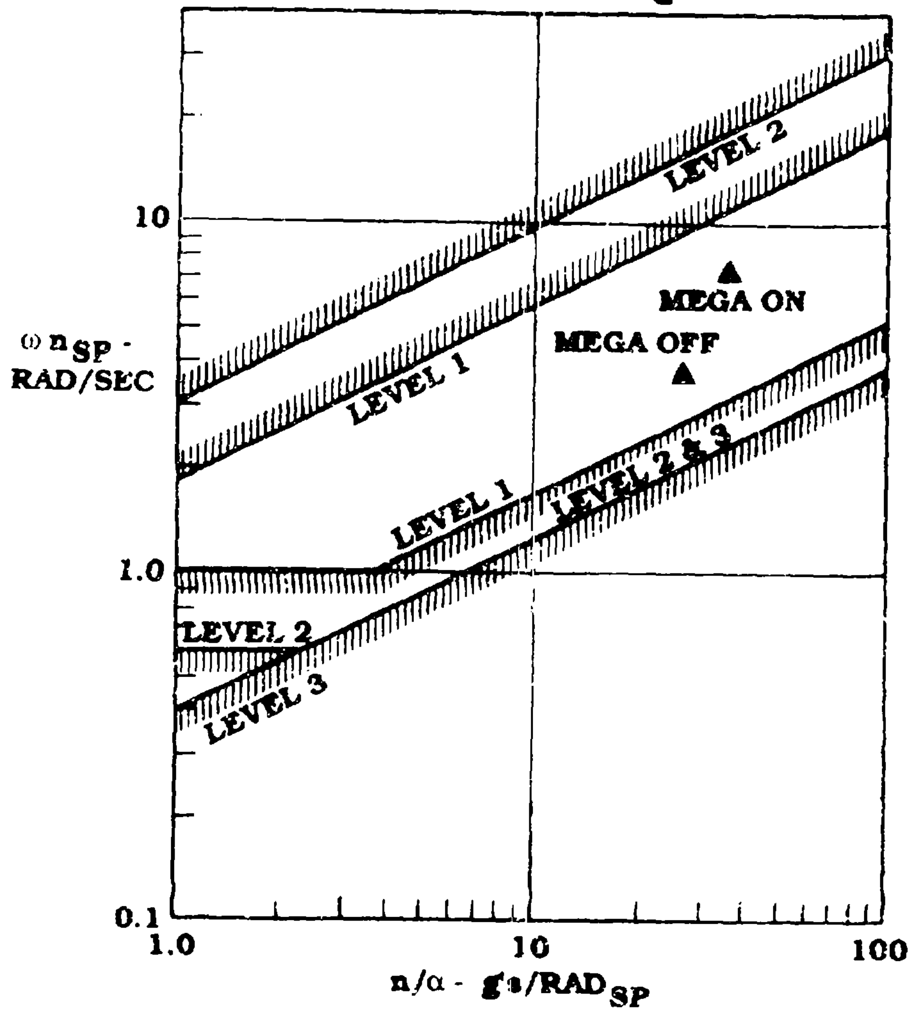

FIGURE 7.3-21 COMMAND RESPONSE COMPARING TRIM CONDITIONS OF 1.0 g and 4.0 g AT MACH .6, 200 ft.

# RMS VERTICAL TURBULENCE RESPONSE AT COCKPIT (INTENSITY: 5 FT/SEC)



BOEING ADVANCED SYSTEMS

# AFTI/F-111 EQUIVALENT SHORT-PERIOD PARAMETERS AND REQUIREMENTS



# AFCS SIMULATION

Joseph M. Hall
Boeing Advanced Systems

# AFTI/F-111 Flight Simulator
# Major Features

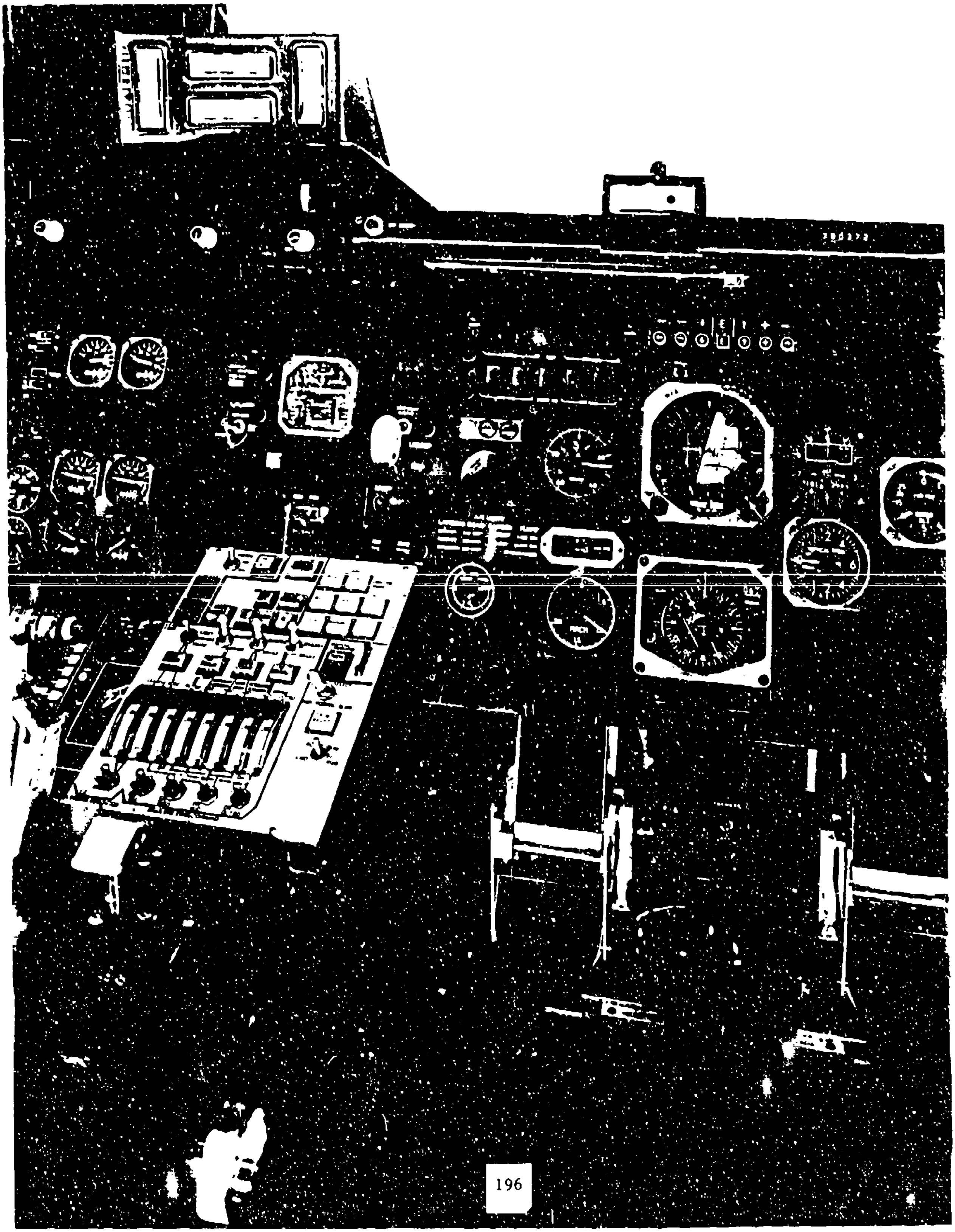
I FIXED BASE, VISUAL FLIGHT SIMULATOR

II TV PROJECTION ON 14 X 20 FT SCREEN

- LANDING RUNWAY
- COMPANION AIRPLANE FOR FORMATION/REFUEL
- HORIZON AND TARGET AIRPLANE FOR LARGE SCALE MANEUVERS (NO LIMITATIONS ON MANEUVERS)

III HIGH FIDELITY REPRESENTATION OF NONLINEAR AERODYNAMIC EFFECTS AND STICK FORCES

IV ALL MAW CONTROL MODES PROVIDED, AS WELL AS SELECTED F-111 CONTROL SWITCH FUNCTIONS



# Flight Simulator Evaluation of Flying Qualities of AFCS Modes

| MODE(S) | DATE(S) OF EVALUATION | | PILOT(S) |
|---|---|---|---|
| | FULL SIMULATION | HARDWARE-IN LOOP | |
| MCC | 1-28-83; 6-10-83 | 4-23-86 | ENEVOLDSON, BIRK |
| MEGA | 7-21-83; 9-15-83 | 4-23-86 | ENEVOLDSON, BIRK, RUFSVOLD |
| MLC | 4-15-83; 6-10-83 | 4-23-86 | ENEVOLDSON, BIRK, SMITH |
| CCC | | 4-30-86 | (NONE) |
| MCC + MEGA | 9-15-83 | 4-23-86 | ENEVOLDSON, BIRK |
| MCC + MLC | 4-15-83; 6-10-83 | 4-23-86 | ENEVOLDSON, BIRK, SMITH |
| MEGA + MLC | | 4-23-86 | ENEVOLDSON |

RESULTS: ACCEPTABLE, WITH NO CONTROLLABILITY PROBLEMS

REFERENCES: 1) BOEING DOCUMENT D365-10041-1, REV. F (5-28-85)

2) BOEING LETTER L-8940-0086-021 (4-25-86)

TABLE 5-42
PILOT EVALUATION OF FLYING QUALITIES
IN LARGE PITCH AND ROLL MANEUVERS
(Effects of MLC)

| DATE | MACH. NO. | ALT. (FT) | LE/TE (DEG) | FCS MODE(S) | PILOT | PILOT COMMENTS |
|---|---|---|---|---|---|---|
| 6-10-83 | .75 | 5000 | 10/17 | MAN | C | |
| ↓ | ↓ | ↓ | ↓ | MAN + MLC | ↓ | No noticeable difference in flying qualities with MLC on. |
| ↓ | ↓ | ↓ | VARIABLE | MCC | ↓ | |
| ↓ | ↓ | ↓ | ↓ | MCC + MLC | ↓ | No noticeable difference in flying qualities with MLC on. |
| 6-10-83 | .9 | 14000 | 10/17 | MAN | C | |
| ↓ | ↓ | ↓ | ↓ | MAN + MLC | ↓ | Again, no noticeable difference with MLC on. |
| ↓ | ↓ | ↓ | VARIABLE | MCC | ↓ | |
| ↓ | ↓ | ↓ | ↓ | MCC+ MLC | ↓ | Seems slightly move stiff in pitch with MLC on. |

X-DC/L7130/JMH
DISK 1/PP1/307-4

D-365-10041

TABLE 5-43
PILOT EVALUATION OF FLYING QUALITIES IN MEGA MODE
FORMATION/REFUEL TASK
WING SWEEP = 26 DEG
15,000 FT.

| DATE | MACH NO. | FCS MODES | COOPER-HARPER RATINGS LAT. | COOPER-HARPER RATINGS LONG. | PILOT | PILOT COMMENTS |
|---|---|---|---|---|---|---|
| 9-15-83 | .6 | MCC | 3.5 | 4 | C | (None) |
| ↓ | ↓ | MCC + MEGA | 3 | 4 | ↓ | With MEGA on, there is a little tendency to overcontrol in pitch. |
| | .8 | MCC | 2 | 3 | | Laterally pretty good. Longitudinally it's a 3. |
| | ↓ | MCC + MEGA | 2 | 3 | | Laterally good. In pitch, the initial response is a little quicker. For rapid inputs, a slight tendency to overcontrol. |
| | .9 | MCC | 3 | 3 | | Laterally, good response. Longitudinally, good, with very little tendency to overcontrol. |
| | ↓ | MCC + MEGA | 2.5 | 4 | | Laterally, good. In pitch, response is good for small inputs. For moderate inputs and tight tracking, there is a slight overcontrol tendency. |

# Summary of Results of AFCS Mode Evaluations

I COOPER-HARPER RATINGS

- LATERAL RATINGS

  BETWEEN 2 (NEGLIGIBLE DEFICIENCIES)
  AND 4 (MINOR BUT ANNOYING DEFICIENCIES)

- LONGITUDINAL RATINGS

  BETWEEN 3 (MILDLY UNPLEASANT DEFICIENCIES)
  AND 4 (MINOR BUT ANNOYING DEFICIENCIES)

II PIO RATINGS

- NO TENDENCIES TOWARDS PILOT INDUCED OSCILLATIONS WERE NOTED DURING ANY AFCS EVALUATION

III CONTROLLABILITY

- SLIGHT TENDENCY TO OVERCONTROL IN TIGHT TRACKING TASKS NOTED FOR MEGA MODE

# Evaluation of Failures Affecting AFCS

CATEGORY I - FAILURES WHICH CAUSE DISENGAGEMENT OF MODE

- FUNCTIONAL VERIFICATION PERFORMED IN SOFTWARE VERIFICATION TESTS (D365-10088-2)
- VERIFICATION OF SWITCHING TRANSIENTS PERFORMED ON FLIGHT SIMULATOR (5-9-86, NEXT SLIDE)

CATEGORY II - FAILURES WHICH DO NOT CAUSE DISENGAGEMENT OF MODE

- FAILURES ARE ADS FAILURES GIVING ±HARDOVER SIGNALS TO:

  MACH NUMBER

  DYNAMIC PRESSURE

  TRUE AIRSPEED
- VERIFICATION OF SWITCHING TRANSIENTS PERFORMED ON FLIGHT SIMULATOR (10-13-83)

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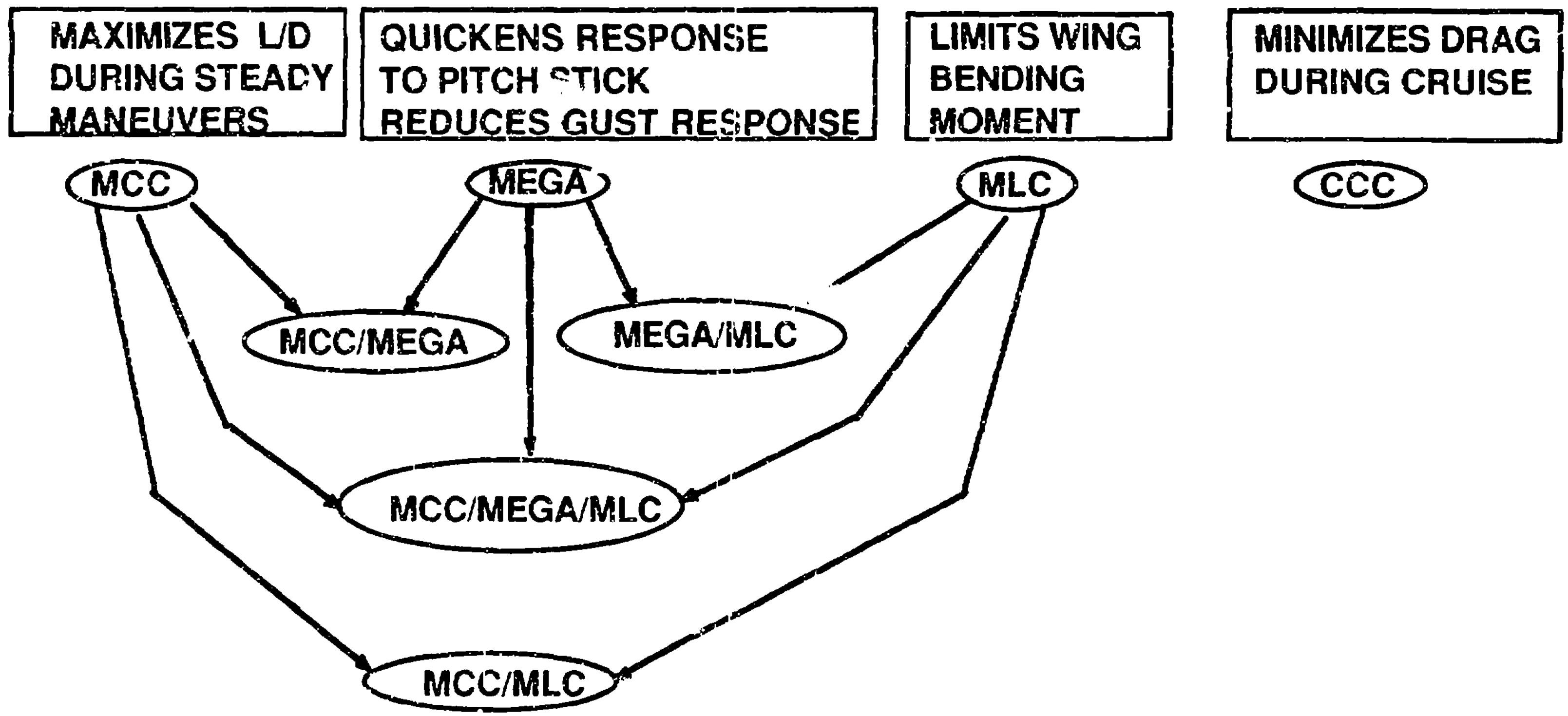
# AFCS MODE COMBINATIONS



BOEING

NUMBER
REV LTR

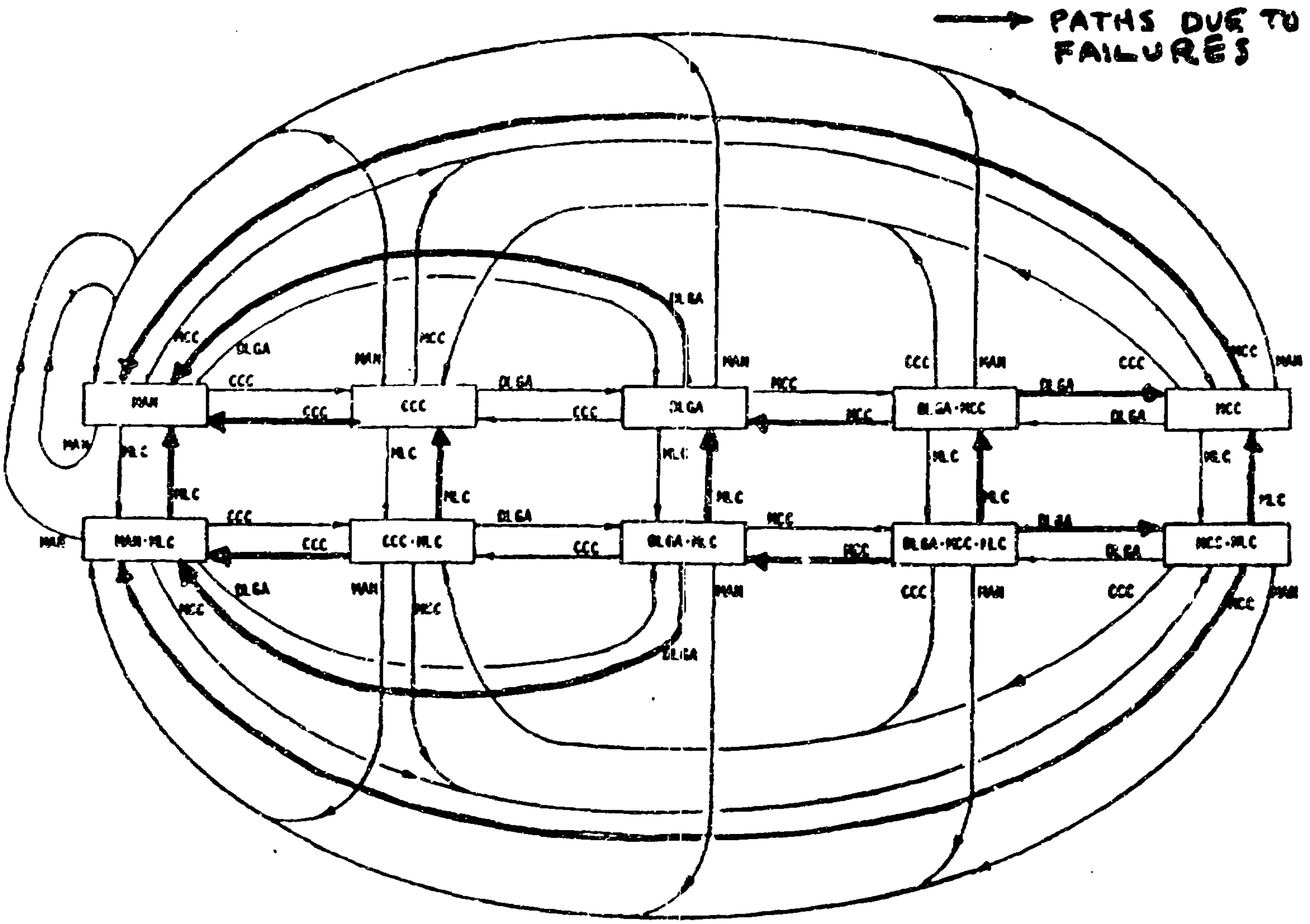



FIGURE 3.3.3-3 MODE SWITCHING TRANSITIONS

SHEET



23

# Failures of Air Data System

| Mode | Failure | Pilot Comments |
|---|---|---|
| MCC | Q = 0 at 1G | Minor Pitch Change |
| | M = 0 at 4G | " |
| | Q&M = 0 at 4G | " |
| MAN + MLC | Q & M = 10,000 at 4G | No noticeable motion |
| | Q & M = 0 at 4G | dropped about 0.5G at failure, but damps out quickly |
| | TAS = 0 | No problem |
| MEGA | TAS = 0 | No significant change |

Limiter on Q: 100 - 1200
Mach: .25 - .95 (Sweep 26)
1.05 - 2.2 (Sweep 58)
TAS: >200

# AFCS Flight Simulator Results Relative to MIL-F-8785B

| PARA. | SUBJECT | RESULTS |
|---|---|---|
| 3.2.1.1 | LONGITUDINAL STATIC STABILITY | STABLE AT ALL TRIM CONDITIONS |
| 3.2.1.1.2 | PITCH FORCE VARIATIONS IN RAPID SPEED CHANGES | NOT SPECIFICALLY ADDRESSED |
| 3.2.1.2 | PHUGOID STABILITY | NO PROBLEMS NOTED ON SIMULATOR |
| 3.2.2.1.3 | RESIDUAL OSCILLATIONS | NO RESIDUAL OSCILLATIONS DETECTED |
| 3.2.2.2.1 | CONTROL FORCES IN MANEUVERING FLIGHT | STICK FORCE PER G IN MCC AND MCC + MEGA NOTED AS LIGHT BUT ACCEPTABLE |
| 3.2.2.2.2 | CONTROL MOTIONS IN MANEUVERING FLIGHT | NO ADVERSE COMMENTS |
| 3.2.2.3 | LONGITUDINAL PILOT INDUCED OSCILLATIONS | NO PIO TENDENCIES NOTED |
| 3.2.2.3.1 | TRANSIENT CONTROL FORCES | NO ADVERSE COMMENTS OTHER THAN NOTED FOR 3.2.2.2.1 |
| 3.2.3.1 | LONGITUDINAL CONTROL IN UNACCELERATED FLIGHT | NO PROBLEMS NOTED ON SIMULATOR (COMPLIANCE SHOWN BY 1G TRIM DATA) |

# FABRICATION & GROUND TESTING OF AFCS

Ciete M. Boldrin
Boeing Advanced Systems

# MANUAL MAW ELECTRONICS CONVERSION TO AFCS OVERVIEW

- **THE MANUAL FLIGHT CONTROL ELECTRONICS UNITS (FCEUs) WERE DESIGNED FOR UPGRADE TO AFCS CONFIGURATION THROUGH HARWARE ADDITIONS.**
  - MINIMIZED CIRCUIT REPLACEMENT
  - RETAINED THE MANUAL MAW CAPABILITY
- **AFCS MODIFICATIONS REQUIRED TWO OF THE THREE AVAILABLE SPARE FCEU CARD SLOTS PLUS SOME MINOR SCALING CHANGES ON SEVERAL MANUAL CARDS.**

**FCEU PACKAGING FEATURES:**

- CUSTOM-DESIGNED RUGGED "FULL ATR LONG" CHASSIS
- CHASSIS BACKPLANE WAS MACHINE WIRE WRAPPED FOR EASY MODIFICATION
- TWO PINS WERE PROVIDED BETWEEN CIRCUIT CARDS AND BACKPLANE FOR CRITICAL SIGNALS
- CIRCUIT CARDS:
  - VIBRATION STIFFENED 8X9 INCH BOARDS
  - WIRE WRAPPED FOR EASY MODIFICATION
  - CAPTAN/TEFLON WIRE WRAP INSULATION REDUCED CUT THROUGHS
  - ALL ELECTRICAL COMPONENTS EXCEPT MEMORY WERE SOLDERED AND CONFORMAL COATED
  - REMOVEABLE MEMORY COMPONENTS WERE HELD IN SOCKETS BY RETENTION PLATES

**AFCS REDUNDANCY MANAGEMENT PHILOSOPHY:**

- DUAL REDUNDANT FAIL PASSIVE AFCS, MANUAL AND ANALOG BACKUP MODES
- AFCS FAILS TO MANUAL DIGITAL MODE, NOT DIRECTLY TO ANALOG BACKUP

**HARDWARE CONFIGURATION CONTROL:**

- USED THE BOEING IRSO SYSTEM WHICH ASSIGNED NEW PART NUMBERS FOR EVERY HARDWARE, SOFTWARE OR HARDWARE ACCEPTANCE TEST CHANGE

# SUMMARY OF MAW AUTOMATIC FLIGHT CONTROL HARDWARE CHANGES TO F-111

- **ADDITIONS TO FCEU:**

  - **AUTOMATIC PROCESSOR COMPUTER CARD**
    - PHYSICALLY IDENTICAL (EXCEPT FOR EPROM MEMORY CONTENT) TO MANUAL COMMAND PROCESSOR COMPUTER CARD
    - CONTAINS PROGRAM MEMORY FOR MCC, MLC AND ME/GA AUTOMATIC MODES

  - **AUTOMATIC STABILON INTERFACE / COMPUTER MEMORY EXPANSION CARD**
    - TRANSMITS STABILON COMMAND SIGNALS TO PITCH DAMPER SERVO
    - PITCH RATE AND NORMAL ACCELERATION BENDING MOMENT ANALOG NOTCH FILTERS
    - SAMPLE AND HOLD ANALOG CIRCUITS FOR LONGITUDINAL ACCELERATION SIGNALS
    - ADDITIONAL 20K EPROM MEMORY FOR BOTH MANUAL AND AUTOMATIC PROCESSOR COMPUTER CARDS

  - **ADDITONAL SENSORS FOR AUTOMATIC MODES / LOCATION ON AIRPLANE / MODES SUPPORTED:**
    - MACH / TACH CADC / MCC, MLC
    - AIRSPEED / TACT CADC / MLC, ME/GA
    - FUEL QUANTITY / TACT INT-DEV TOT / MCC, MLC
    - PITCH STICK / COCKPIT / CCC, ME/GA
    - PITCH RATE / TACT PTICH RATE GYRO / ME/GA
    - NORMAL ACCELERATION / F.S. 460 / MCC, MLC
    - NORMAL ACCELERATION / TACT ACCELEROMETER / ME/GA
    - ROLL ATTITUDE / TACT SPU, MD3-3 / CCC, ME/GA
    - LONGITUDINAL ACCEL / F.S. 460 / CCC
    - ROLL ACCELERATION / F.S. 460 / MLC
    - ROLL RATE / TACT ROLL RATE GYRO / MLC
    - STABILON POSITION / TACT STABILONS / MLC

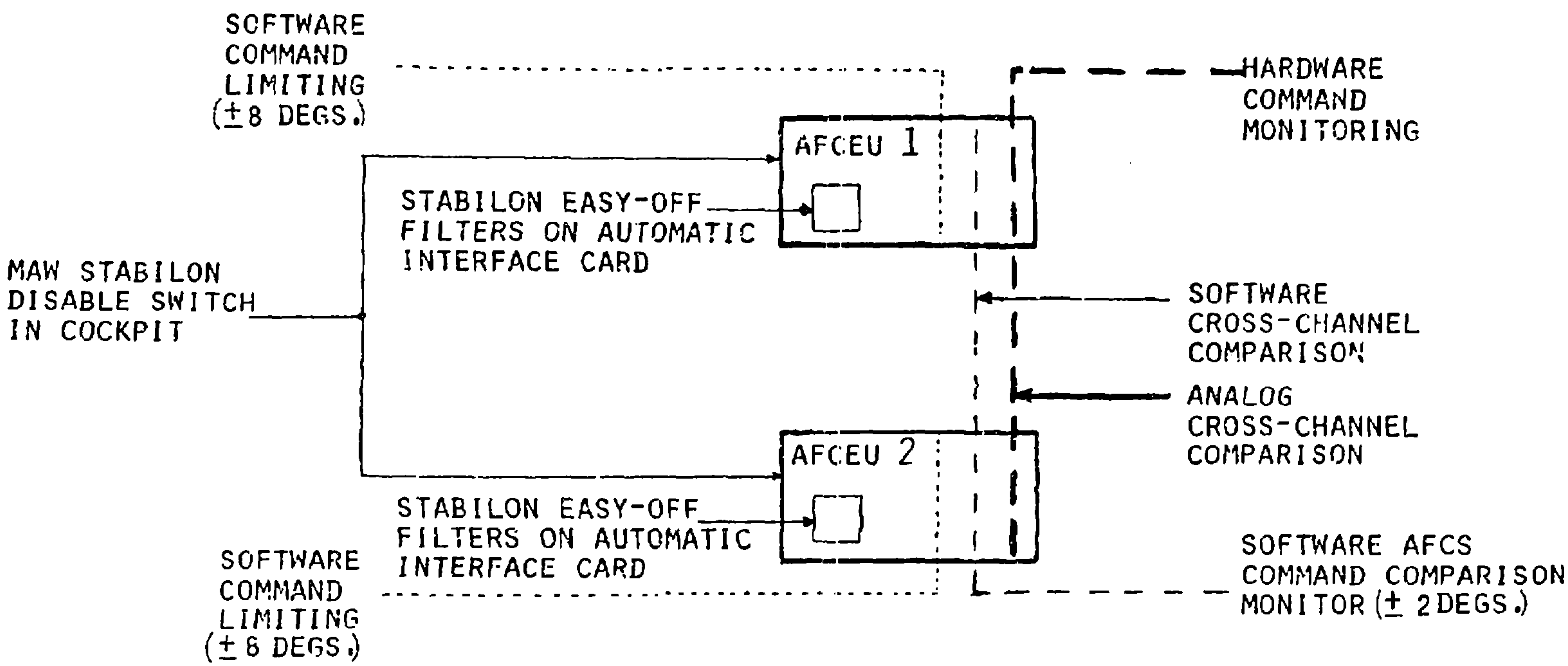
  - ***ADDITION TO MAW CONTROL AND DISPLAY PANEL***
    - MAW STABILON DISABLE SWITCH

  - **ADDITIONS TO AIRCRAFT WIRING**
    - WIRING BETWEEN FCEU AND C&D PANEL MAW STAB DISABLE SWITCH
    - WIRING BETWEEN FCEU AND AUTOMATIC SENSORS
    - WIRING BETWEEN FCEU AND TACT PITCH FCS

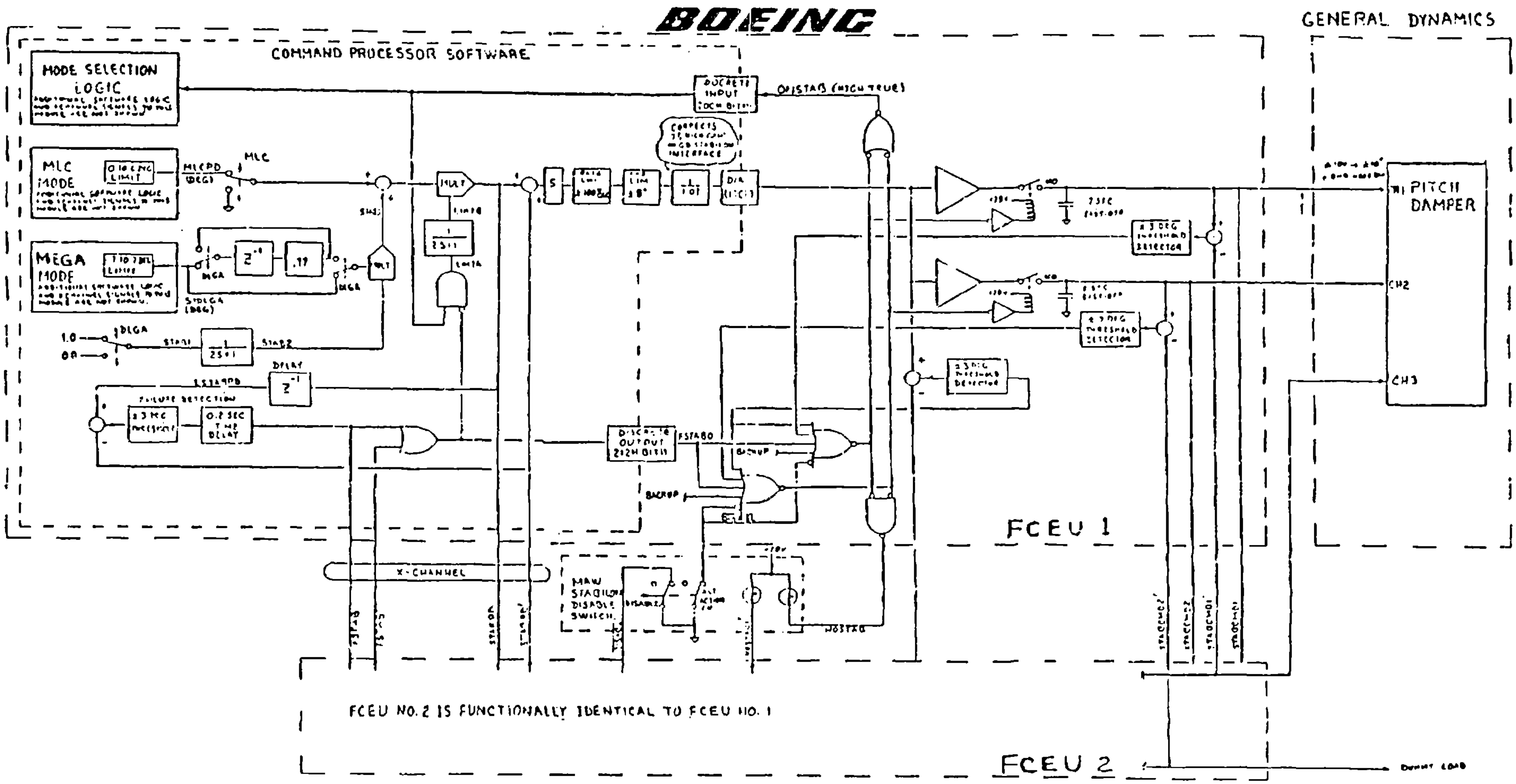
  - **CHANGES TO THE DDIU**
    - REVISED DOWNLINK SERIAL FORMAT
    - ADDED DDIU ALIVENESS MONITOR LIGHT
    - INCREASED CROSS CHANNEL SERIAL DATA RATE FROM 150K TO 400K BITS/SEC

# AFCS DESIGN SAFETY FEATURES

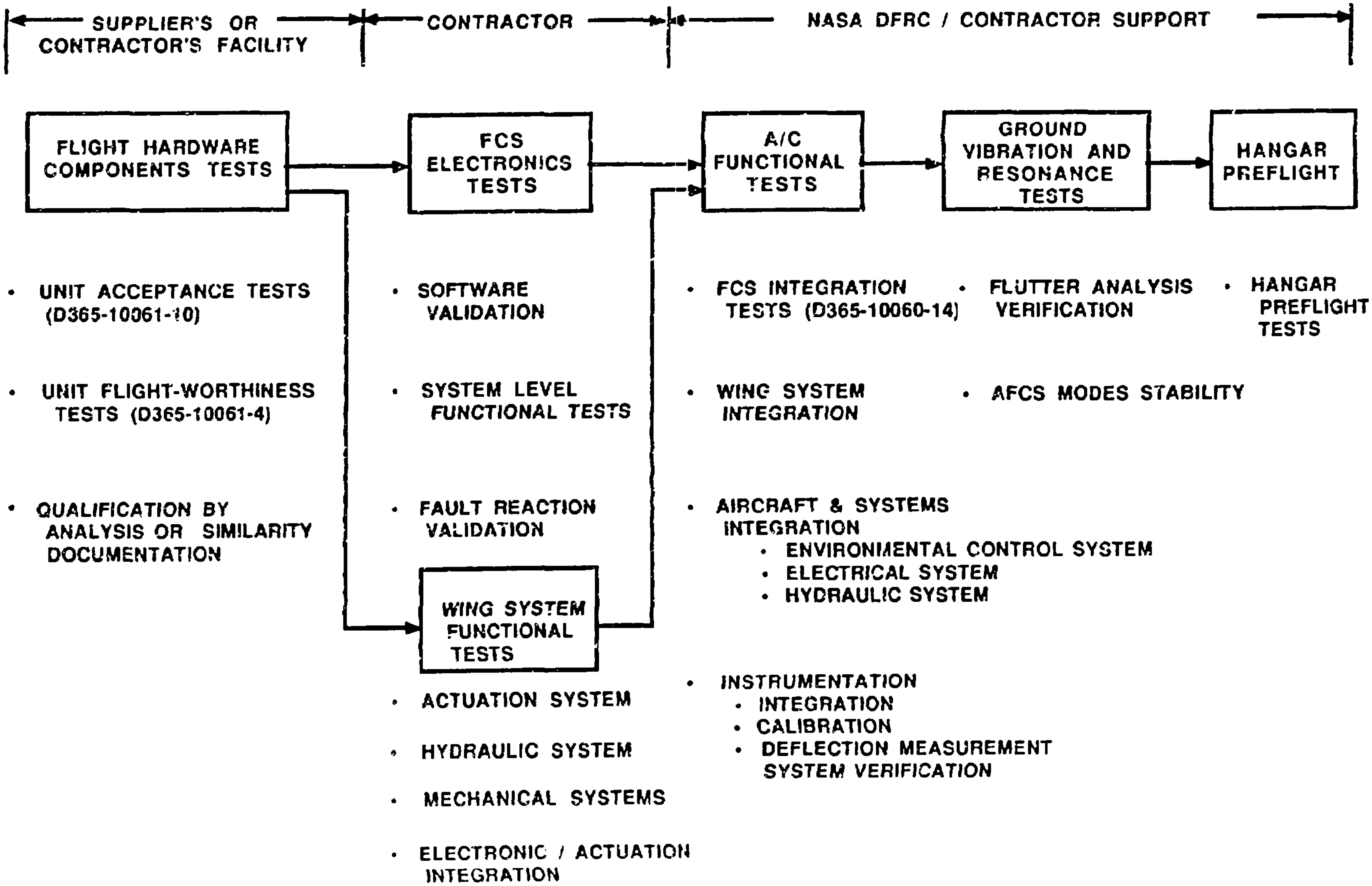
| FAILURE ITEM | AUTOMATIC ACTIONS | ANNUNCIATION |
|---|---|---|
| • STABILON ANALOG COMMAND SIGNAL FAILURE | • BOTH SOFTWARE AND HARDWARE COMPARE STABILON COMMANDS OF BOTH FCEU'S, AND, IF GREATER THAN THREE DEGREES MISMATCH, INDEPENDENTLY SET THE STABILON COMMAND OUTPUT TO ZERO DEGREES. | • MAW STAB DISABLE ANNUNCIATOR ON C&D PANEL |



# TRIPLEX STABILON INTERFACE



# AIRCRAFT HARDWARE CHECKOUT AND TEST



# FCEU HARDWARE ACCEPTANCE TEST DESCRIPTION
# (D365-10061-10)

PURPOSE: FCEU HARDWARE PERFORMANCE VERIFICATION PRODUCTION SCREEN

DESCRIPTION: AN EXTERNAL HOST COMPUTER CONTROLLED THE FCEU's OWN I/O TO STIMULATE A SECTION OF CIRCUITRY AND THEN VERIFIED THE RESPONSE AGAINST SPECIFIC PASS / FAIL CRITERIA.

SCOPE: PROVIDED A COMPLETE HARDWARE VERIFICATION TEST FOR MANUAL, BACKUP AND AUTOMATIC FLIGHT CONTROL ELECTRONICS WITHIN A SINGLE FCEU.

- CONSISTED OF 60 SEMI-AUTOMATIC TESTS

THE FOLLOWING AFCS CIRCUITS WERE TESTED:

- AUTOMATIC PROCESSOR
  - MEMORY & I/O
  - MANUAL & AUTO PROCESSOR SERIAL I/O INTERFACE
- AUTOMATIC INTERFACE ELECTRONICS
  - STABILON & DISENGAGE CIRCUIT
  - ANALOG PITCH RATE & NORMAL ACCELERATION BODY BENDING NOTCH FILTERS
  - SAMPLE & HOLD ANALOG CIRCUITS FOR LONGITUDINAL ACCELERATION SIGNALS

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# HARDWARE ACCEPTANCE TEST SUMMARY

- 60 TOTAL TESTS PER FCEU
- 20 PRIMARY SYSTEM TESTS
- 35 BACKUP SYSTEM TESTS
- 5 AUTOMATIC SYSTEM TESTS
- TESTS WERE RUN WITH FLIGHT EPROMs INSTALLED
- TESTING DEFINED IN D365-10061-10
- TEST RESULTS PRINTED OUT WITH PASS / FAIL AND TOLERANCE EXCEEDANCE DATA IF APPLICABLE
- TEST REPORT EASY TO FOLLOW SINCE RESULTS IMMEDIATELY FOLLOW SET UP PROCEDURES
- TESTS WERE DESIGNED TO BE EFFICIENT FAULT ISOLATION TOOL

# FCEU FLIGHT WORTHINESS TEST DESCRIPTION
# (D365-10061-4)

**SUMMARY:** SINUSOIDAL / RANDOM VIBRATION AND THERMAL CYCLING TESTS (-65 DEG F TO + 160 DEG F, 10 CYCLES MINIMUM) WERE CONDUCTED. ▷

**PURPOSE:** THE FLIGHT WORTHINESS TESTS SERVED A PRODUCTION SCREENING FUNCTION AND ALSO VERIFIED ELECTRICAL HARDWARE OPERATION AFTER EXPOSURE TO ENVIRONMENTAL EXTREMES. THE TESTS WERE SIMILAR TO THOSE WHICH WERE CONDUCTED ON THE MANUAL FCEU's.

**TEST FACILITIES:**

AN AUTO-CONTROL LABORATORIES ENVIRONMENTAL CHAMBER WAS USED TO CONDUCT THE VIBRATION AND THERMAL CYCLING TESTING.

▷ ALTITUDE TESTS WERE NOT CONDUCTED ON THE FCEU's BECAUSE THE PRIMARY PROBLEMS UNCOVERED DURING ALTITUDE TESTING ARE RELATED TO THE INCREASED TEMPERATURE OF THE ELECTRONICS CAUSED BY DECREASED EFFECTIVENESS OF COOLING AIR AT HIGHER ALTITUDES. TESTS OF THE MAW FCEUs HAVE VERIFIED THAT THEY OPERATE WITHOUT DEGRADATION FOR AT LEAST ONE-HALF HOUR WITHOUT COOLING AIR.

THE MAW SYSTEM DOES NOT EMPLOY HIGH VOLTAGE SUBJECT TO BREAKDOWN AT ALTITUDE.

# FLIGHT CONTROL SYSTEM INTEGRATION TEST DESCRIPTION FOR THE AUTOMATIC SYSTEM (D365-10060-14)

PURPOSE:

- VERIFIED MECHANICAL, ELECTRICAL AND HYDRAULIC OPERATION OF THE ENTIRE FCS AFTER INSTALLATION ON THE AIRPLANE
- VERIFIED AFCS SENSOR AND STABILON INTERFACE OPERATION
- VERIFIED OPERATION OF THE AUTOMATIC MODES

DESCRIPTION:

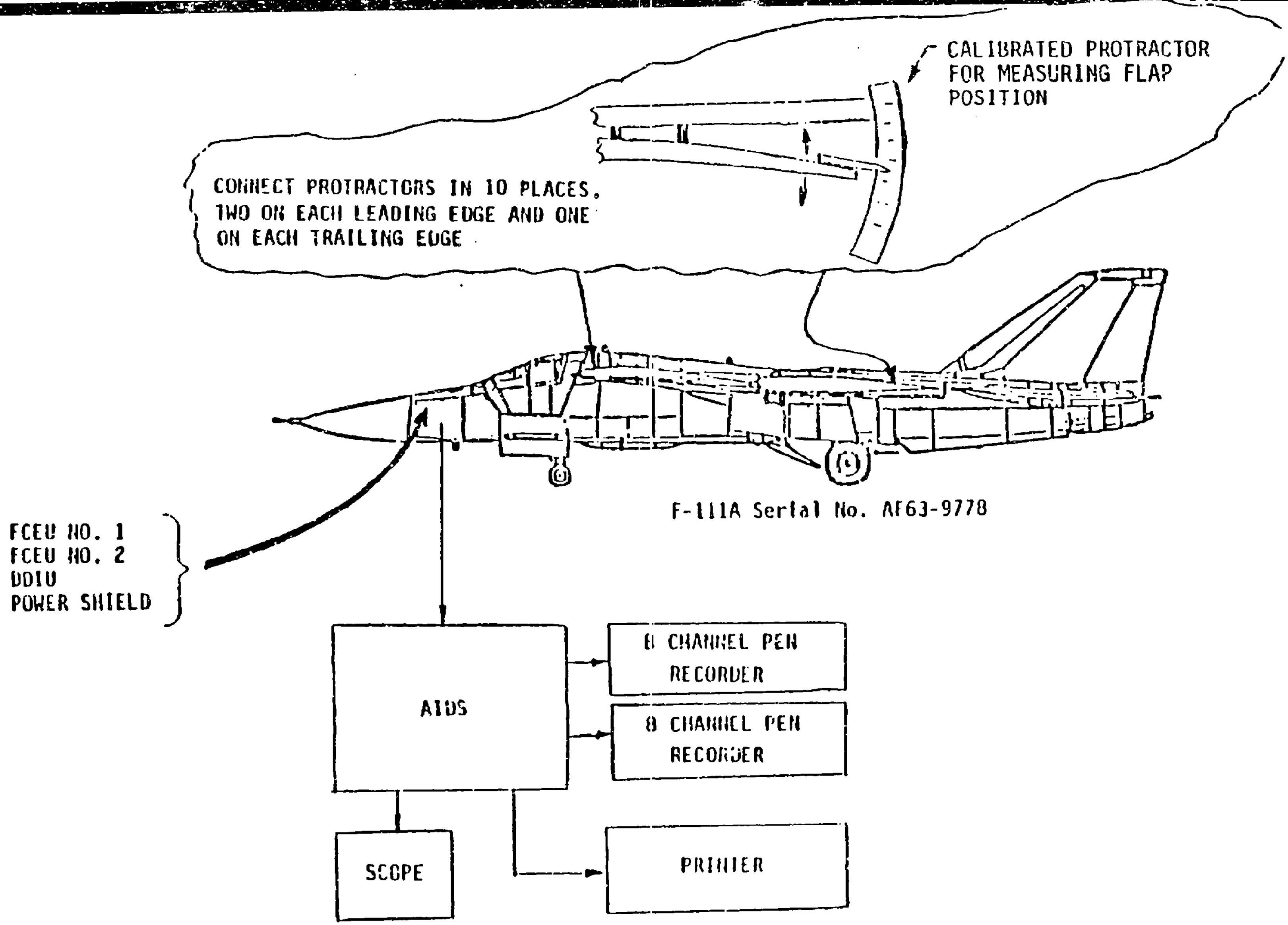
THE TESTS WERE RUN FROM MANUAL TEST PROCEDURES USING A NASA FURNISHED AIRCRAFT INTERROGATION DISPLAY SYSTEM TO MONITOR SYSTEM PERFORMANCE.

THE FLIGHT CONTROL SYSTEM INTEGRATION TEST FOR THE MANUAL SYSTEM WAS RERUN WITH THE FOLLOWING ADDITIONAL TESTS FOR THE AUTOMATIC SYSTEM:

- AUTO MODE TESTS WITH 26, 40* AND 58 DEGREE WING SWEEP (MCC, MEGA, MLC AND CCC MODES)
- AUTO MODE SELECTION LOGIC TESTS
- DDIU TRANSMISSION TESTS OF AUTOMATIC SIGNALS

*40 DEGREE WING SWEEP AUTO MODE TESTS WERE INSERTED IN D365-10060-14 TO VERIFY THAT THE AUTO MODES DO NOT ENGAGE AT 40 DEGREE WING SWEEP

# SYSTEM INTEGRATION TEST EQUIPMENT SETUP



# SYSTEM INTEGRATION TEST SUMMARY

- 253 TOTAL TESTS
- 87 PRIMARY TESTS
  SYMETRIC AND ROLL COMMANDS, FAILURE DETECTION, ANNUNCIATORS, PREFLIGHT TEST, WING SWEEP AND FLAP RATE.
- 87 BACKUP SYSTEM TESTS
  SYMETRIC AND ROLL COMMANDS, WING SWEEP AND FLAP RATES.
- 8 PRIMARY / BACKUP TRANSITION
- 40 SURFACE BRAKE TESTS
  SURFACE PAIRS, INDIVIDUAL BRAKES AND ELECTRICAL COMMANDS
- 5 DDIU TESTS
- 26 FLAP SWITCH EFFECTS ON F-111 SYSTEMS

# AFCS FABRICATION AND GROUND TESTING LESSONS LEARNED

- FLIGHT CRITICAL DESIGNS WITH A REMOTE POSSIBILITY OF SINGLE POINT FAILURE ARE UNACCEPTIBLE
- TOLERANCE PROBLEMS MAKE ANALOG CIRCUITS FAR MORE COSTLY THAN DIGITAL CIRCUITS TO DESIGN AND TEST
- GROWTH CAPABILITIES FOR CHANGING REQUIREMENTS ARE ESSENTIAL IN R&D DESIGN
- STABILITY OF THE SOFTWARE ENVIRONMENT FOR ENGR TOOLS AND MFGR AIDS IS CRITICAL TO SUCCESS OF LONG LIVED PROJECTS
- PRODUCTION RULES ARE EXPENSIVE TO IMPLEMENT ON AN R&D PROJECT
- CAPTAN COATED TEFLON WIRE INSULATION GREATLY REDUCES CUT THROUGH SHORTS
- SPECIFYING HARDWARE ACCEPTANCE TEST REQUIREMENTS AS A SEQUENCE OF 'OPERATOR DO THIS', 'PROGRAM DO THAT' INSTRUCTIONS WORKED WELL
- XYBASIC PROGRAMMING LANGUAGE WORKED WELL FOR HARDWARE ACCEPTANCE TESTS

FLIGHT DYNAMICS LABORATORY
AFTI
ADVANCED FIGHTER TECHNOLOGY INTEGRATION

# AFTI/F-111 MISSION ADAPTIVE WING

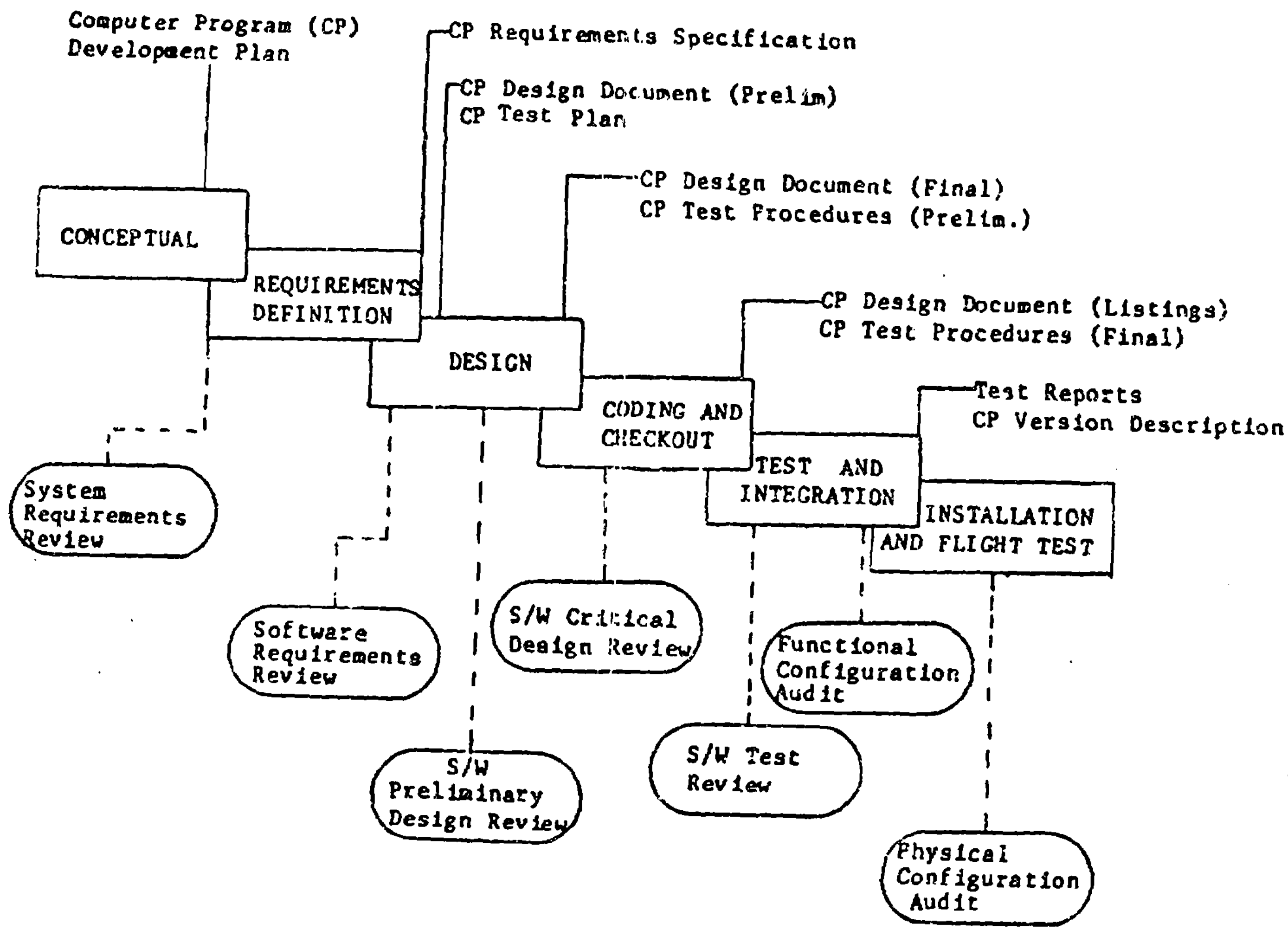
## GOVERNMENT OVERVIEW OF SOFTWARE DEVELOPMENT

RON BRAET

## TOPICS

- SOFTWARE DEVELOPMENT METHODOLOGY
- SOFTWARE DOCUMENTATION
- SOFTWARE TEST OVERVIEW
- SOFTWARE CONFIGURATION CONTROL
- INDEPENDENT SOFTWARE REVIEW ACTIVITIES
- LESSONS LEARNED

## SOFTWARE DEVELOPMENT METHODOLOGY: OVERVIEW




SOFTWARE DEVELOPMENT PROCESS

## SOFTWARE DEVELOPMENT METHODOLOGY: CONSIDERATIONS

- PROJECT ORGANIZATION
  - STAFF RESPONSIBLE FOR SYSTEM/SOFTWARE REQUIREMENTS AND FOR SOFTWARE VERIFICATION/SYSTEM TEST
  - PROJECT RESPONSIBLE FOR SOFTWARE DESIGN AND CODING
  - QA ORGANIZATION SEPARATE FROM PROGRAM

- DOCUMENTATION
  - TYPES OF DOCUMENTATION
  - ALLOCATION OF RESOURCES
  - LIFE CYCLE USE

- PROGRAM LANGUAGE
  - HIGHER ORDER LANGUAGE
  - COMPILER MATURITY
  - ASSEMBLY CODE
  - DEVELOPMENT METHODS & TOOLS

## SOFTWARE DEVELOPMENT METHODOLOGY: CONSIDERATIONS (CONTINUED)

- CONFIGURATION CONTROL
  - REQUIREMENTS ESTABLISHED AND STABILIZED
  - MARGINAL CHANGES/NECESSARY CHANGES
  - AF/NASA INVOLVEMENT
  - TRANSITION COMPATIBILITY
- SAFETY OF FLIGHT
  - REVIEW OF CONTRACTOR STUDIES
  - INDEPENDENT INVESTIGATION
  - MONITORING ACTIVITIES
  - INDEPENDENT REVIEW BOARDS

# SOFTWARE DOCUMENTATION

- o CP REQUIREMENTS SPECIFICATION
- o CP DESIGN SPECIFICATION
- o CP TEST PLAN
- o CP TEST PROCEDURES
- o CP VERSION DESCRIPTION

- SOFTWARE DEVELOPED PER FOLLOWING DOCUMENTS:
  - o D365-10021 AFTI/F-111 MAW FLIGHT CONTROL SYSTEM DEVELOPMENT PLAN
  - o D365-10076-1 AFTI/F-111 SOFTWARE QUALITY ASSURANCE PLAN
  - o D365-23310-1 AFTI/F-111 MAW COMPUTER PROGRAM DEVELOPMENT PLAN

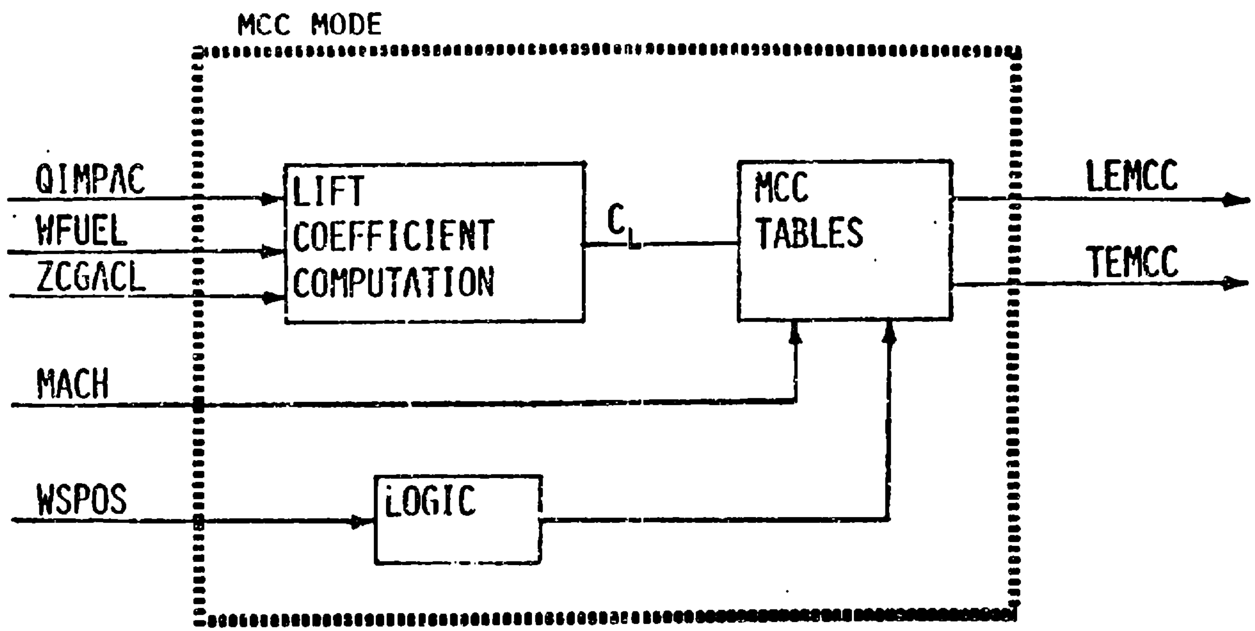
# SOFTWARE TESTING OVERVIEW

- MODULE TESTS
- INTERMODULE COMPATIBILITY TESTS
- VERIFICATION TESTS (DRY RUN) D365-10088-2
- HARDWARE-IN-THE-LOOP TESTS
- VERIFICATION TESTS (FORMAL) D365-10088-2
- AIRCRAFT TESTS D365-10060-14
- FLIGHT TESTS

## MODULE TEST SEQUENCE

- O PREPARE PROGRAM FLOWCHART FROM MODULE LISTING
- O VERIFY THAT THE FLOWCHART SATISFIED THE SOFTWARE REQUIREMENTS
- O DIVIDE THE PROGRAM FLOWCHART INTO TESTABLE SEGMENTS
- O PREPARE A SEPARATE TEST PROCEDURE FOR EACH PROGRAM SEGMENT
- O TEST THE FIRST PROGRAM SEGMENT USING THE "WINDOW" PROGRAM
- O ADD SECOND SEGMENT AND TEST, THEN THIRD, ETC.
- O TESTS DOCUMENTED IN SOFTWARE DEVELOPMENT FOLDERS

SAMPLE MODULE TEST

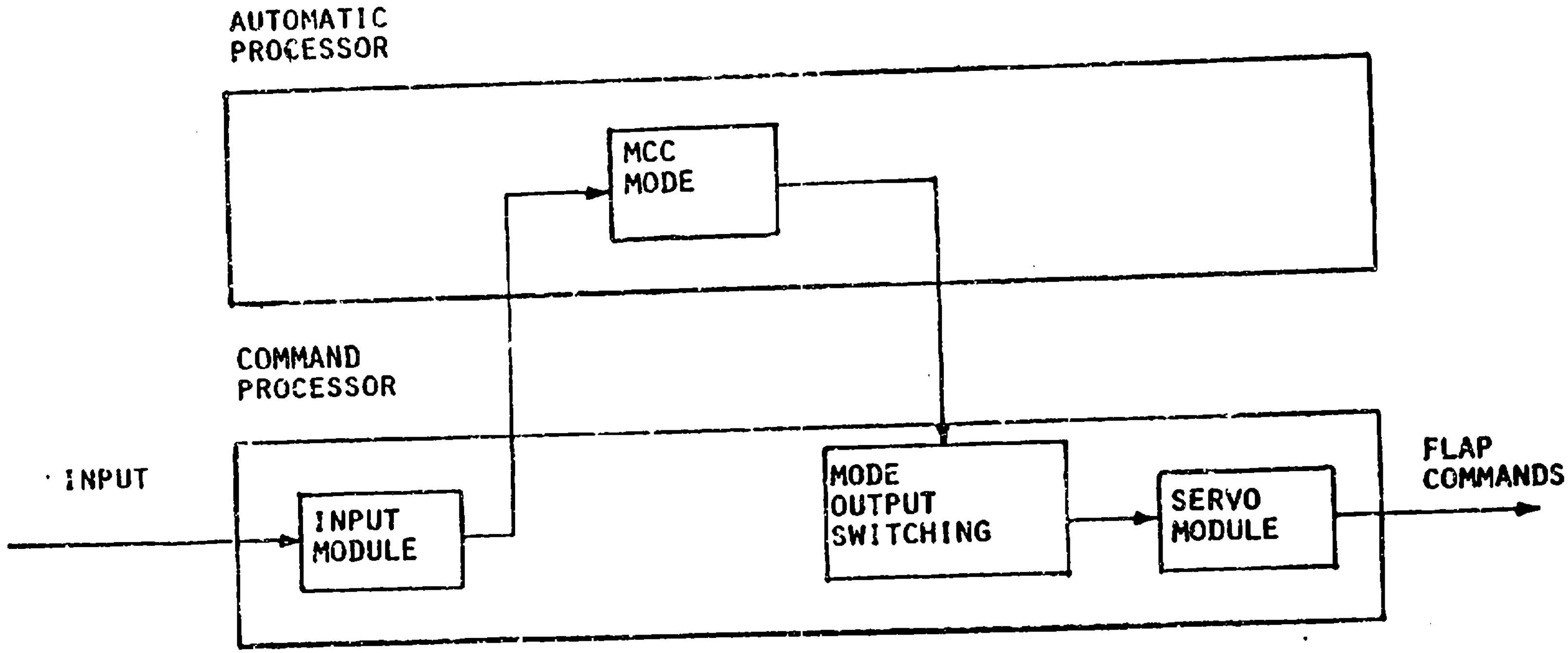



O VERIFY THAT THE OUTPUT SIGNALS ARE CORRECT FOR THE GIVEN INPUT SIGNALS

## INTERMODULE COMPATIBILITY TEST SEQUENCE

- INTEGRATE ALL OF THE MODULES INTO ONE PROGRAM
- EXECUTE THEM IN THE SEQUENCE THEY ARE TO BE EXECUTED IN FLIGHT
- VERIFY THAT THE MODULES INTERACT TO PROVIDE THE EXPECTED OUTPUTS
- IMCT RESULTS DOCUMENTED IN SOFTWARE DEVELOPMENT FOLDERS

SAMPLE INTERMODULE COMPATIBILITY TEST




- VERIFY THAT INTERFACING SIGNALS ARE PASSED BETWEEN THE MODULES.
- VERIFY THAT THE OUTPUT SIGNALS ARE CORRECT FOR THE GIVEN INPUT SIGNALS.
- THE TEST IS CONDUCTED WITH SIMULATORS OF THE TWO PROCESSORS.
- THE SHOWN MODULES AND ALL OTHER MODULES ARE BEING EXECUTED BY THE EXECUTIVES IN THE TWO PROCESSORS.

## SOFTWARE VERIFICATION TESTS

- CONCENTRATE ON:
  - TECHNICAL CORRECTNESS
  - EFFICIENCY
  - TECHNICAL ADEQUACY
- HARDWARE TEST EQUIPMENT SETUP USED TO DRIVE OPEN-LOOP TESTS
- D365-10088-2 WAS PREPARED TO VERIFY THE SOFTWARE REQUIREMENTS SPECIFIED IN D365-10062-1 AND D365-10086-1.

## VERIFICATION TEST PROCEDURES DOCUMENT

- GENERAL DESCRIPTION OF A TYPICAL TEST FOR BACKGROUND PURPOSES
- DOCUMENTATION REFERENCES
- DESIGN REFERENCES
- TEST SETUP DESCRIPTION FOR EACH TEST
- PROCEDURE FOR CONDUCTING EACH TEST
- A DATA SHEET FOR EACH TEST WITH EXPECTED RESULTS AND TOLERANCES

## HARDWARE-IN-THE-LOOP SOFTWARE TESTS

- PILOTED SIMULATION WITH MAW SYSTEM IN HARDWARE OR IN THE SIMULATION EQUATIONS.
- VERIFIED ACTUAL SOFTWARE WITH ALL FOUR AUTOMATIC MODES:
  - MCC
  - MLC
  - MEGA
  - CCC
- MCC, MLC, AND MEGA MODE RESPONSE WAS ESSENTIALLY IDENTICAL WITH THE HARDWARE.
- CCC MODE REVEALED A NOISE PROBLEM WHICH WAS RESOLVED BY RECONFIGURING THE INPUT HARDWARE.
- MEGA AERO DATA PROCESS TIME PROBLEM REQUIRED ARRAY PROCESSOR.

## SOFTWARE CONFIGURATION CONTROL

- O INITIATED AFTER "DRY RUN" SOFTWARE VALIDATION TESTS AND PRIOR TO "DRY RUN" FUNCTIONAL TESTS
- O FORMAL SOFTWARE CONTROL OF "CHIP BURNED" SOFTWARE MAINTAINED BY BY BOEING QUALITY ASSURANCE
- O FORMAL CONFIGURATION CONTROL PASSED TO GOVERNMENT UPON SUCCESSFUL FORMAL ACCEPTANCE TEST OF AIRCRAFT
- O CONFIGURATION MANAGEMENT BOARD (AIR FORCE/NASA) REVIEW/EVALUATE CHANGE AND MAKE RECOMMENDATIONS TO AIR FORCE PROGRAM MANAGER
- O ENGINEERS USE DR PROCESS FOR PREPARING SOFTWARE CHANGES

## INDEPENDENT SOFTWARE REVIEW ACTIVITIES

- O SOFTWARE DEVELOPMENT MONITORING
  - o ATTEND/SUPPORT PROGRAM REVIEWS
  - o WEEKLY SOFTWARE STATUS CONTACT
  - o CONFIGURATION MANAGEMENT PROCEDURES
  - o ON-SITE VISITS
    - SOFTWARE DESIGN WALKTHROUGH (DESIGN FOLDERS)
    - TEST DEMONSTRATION
    - LIMITED SOFTWARE AUDIT
    - CONFIGURATION MANAGEMENT INSPECTION
- O REVIEW OF SOFTWARE RELATED DOCUMENTATION
  - o DEVELOPMENT PLAN
  - o REQUIREMENTS SPECIFICATION
  - o DESIGN DOCUMENT
  - o TEST DOCUMENT
  - o VERSION DESCRIPTION
  - o QUALITY ASSURANCE PLAN
- O SYSTEM LEVEL DOCUMENTATION REVIEW
- O NASA/ADFRF
  - o SIMULATION DEVELOPMENT SUPPORT/INTERFACE
  - o GROUND TEST PLANNING REVIEW

## LESSONS LEARNED

- CONTRACTOR CAN DELIVER GOOD/WORKABLE/MAINTAINABLE SOFTWARE WITHOUT ADHERING TO FULL MIL-STDs

- NO FORMAL DOCUMENTATION OF MODULE/INTERMODULE TESTING

- FUNCTIONAL/ENGINEERING SIMULATION AS DONE BY NASA AIDED IN ASSURING CORRECT FUNCTIONAL DESIGN AND INTERFACE

- SIMULATION TESTING IS ONLY AS GOOD AS THE MODELING ACCURACY

# SESSION IV

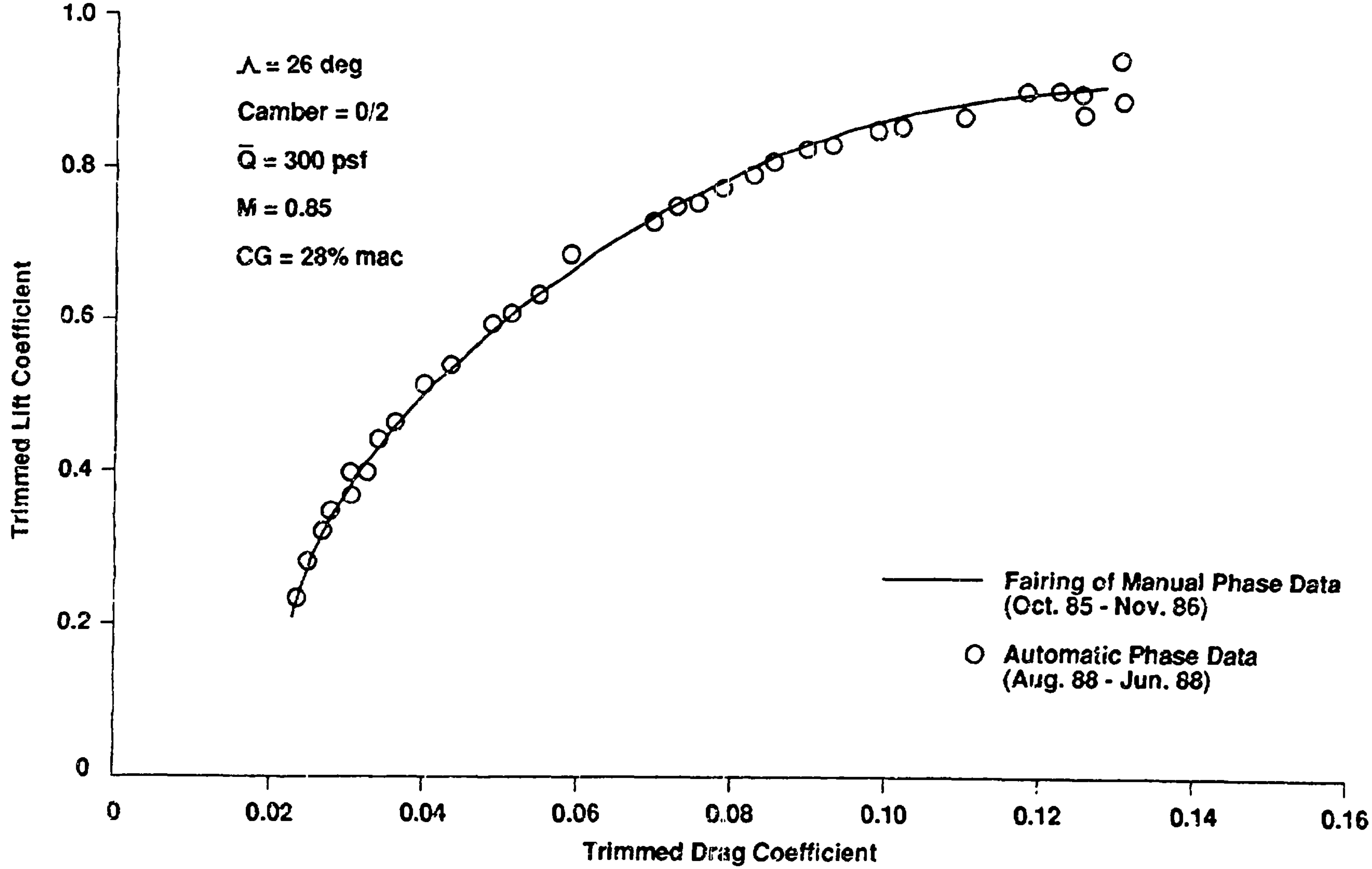
# AUTOMATIC FLIGHT CONTROL SYSTEM FLIGHT TEST RESULTS

# Flight Test Performance

- Automatic Mode Performance
- Quantify Performance Gains/Losses of MAW Automatic Modes
  - MCC
  - MLC
  - CCC
- Performance Maneuvers Included:
  - Roller Coasters (POPU'S)
  - Wind-up Turns
  - Steady Turns

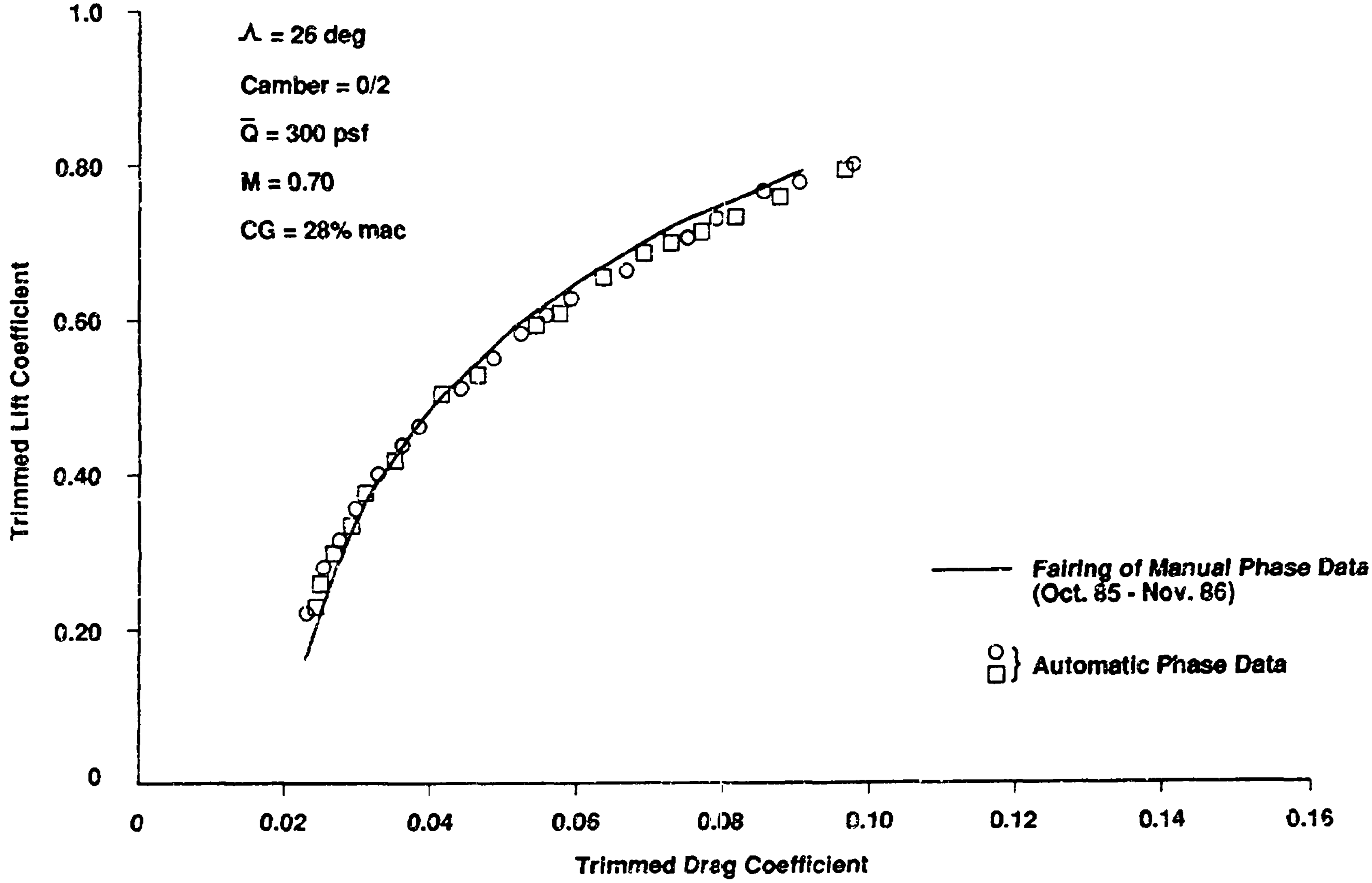
# Roller Coaster Drag Repeatability

## (Manual Mode Phase vs Automode Phase)



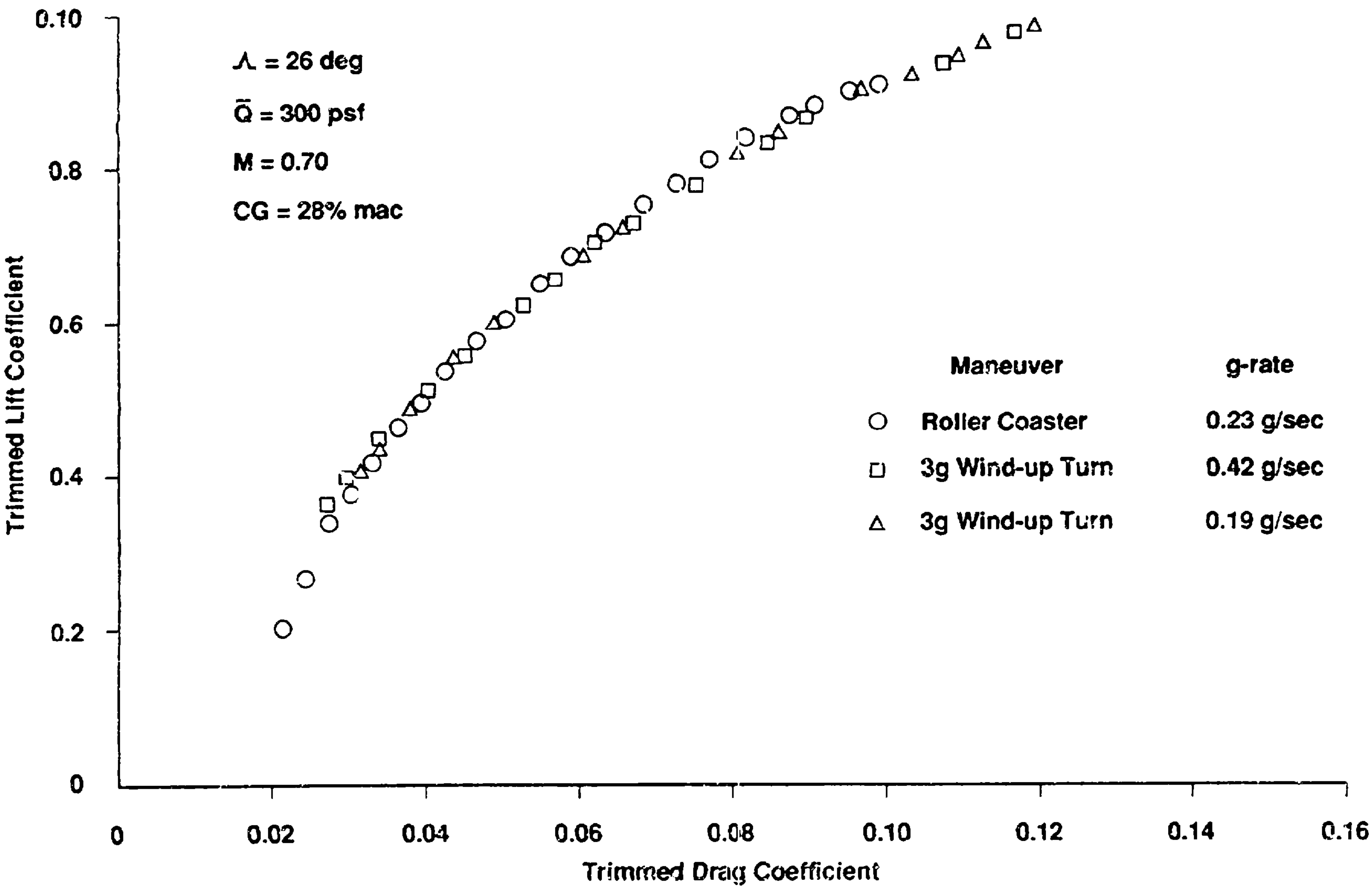
# Roller Coaster Drag Repeatability

## (Manual Mode Phase vs Automode Phase)

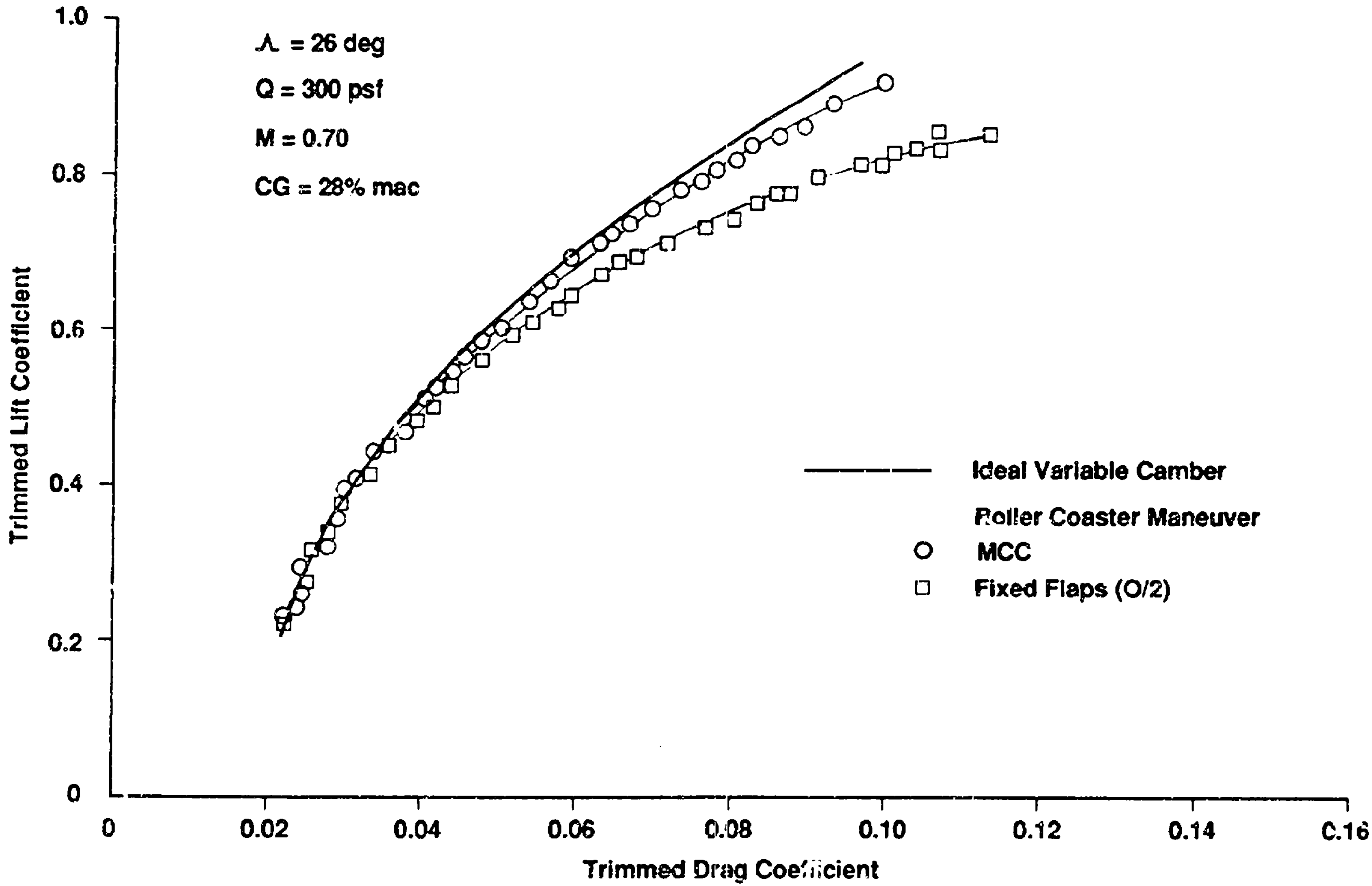


# Dynamic Maneuver/Onset - Rate Effects

## MCC Mode

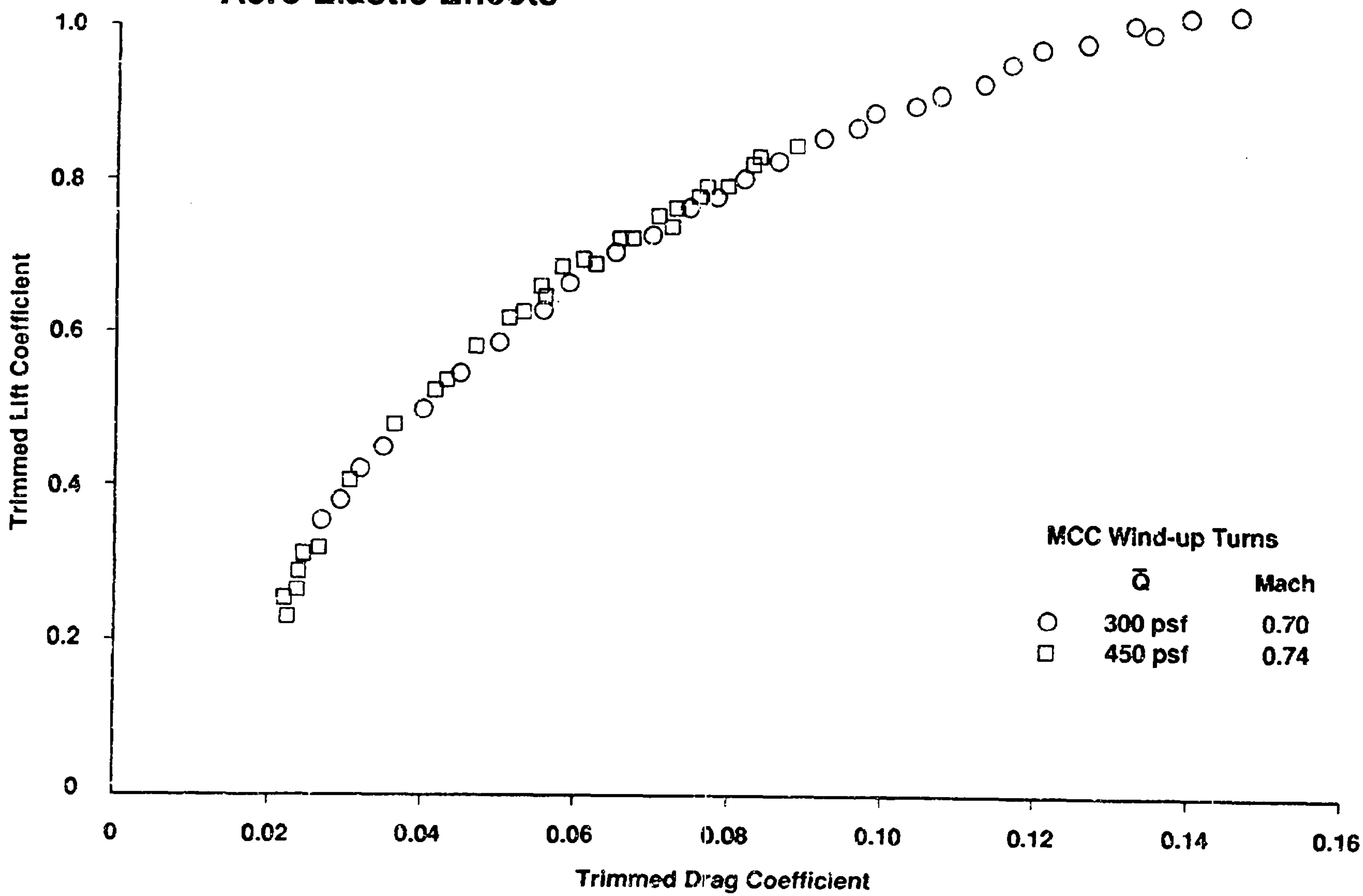


# Roller Coaster Maneuver



# Wind-up Turns

## Aero Elastic Effects



# Performance Summary

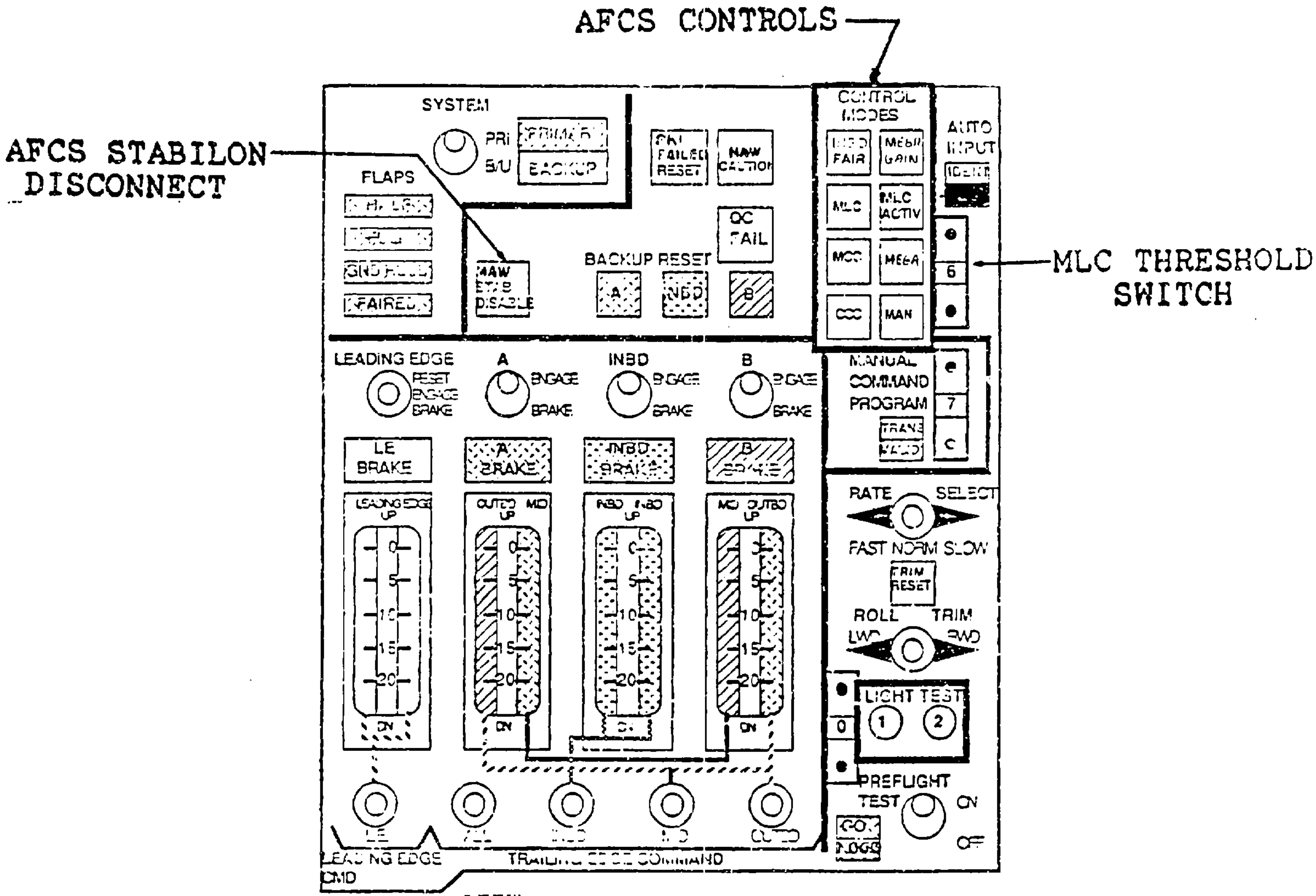
- At Mach = 0.70, $\bar{Q}$ = 300psf the MCC Mode Showed Performance Gains of:
  - 16% Reduction in Drag at 2g's
  - 6.7% Increase in Nz at 2g's

- Dynamic Response
  - Maneuver Rates (load factor onset) Varied from 0.19 to 0.42 g/sec
    - No Detectable Effect on Drag
    - The Noted Differences are Attributed to the Table Look-up Values
    - Additional Data Required

# AFCS FUNCTIONAL AND PERFORMANCE RESULTS

Paul R. Bussing
Boeing Advanced Systems

Paul W. Phillips
Air Force Flight Test Center


AFCS CONTROLS
AFCS STABILON DISCONNECT
MLC THRESHOLD SWITCH
SYSTEM
PRI
S/U
BACKUP
FLAPS
FAIRED
CONTROL MODES
FAIR
MLC
MLC ACTIV
MAN
AUTO INPUT
MAW CAUTION
QC FAIL
BACKUP RESET
A
INBD
B
LEADING EDGE
RESET
ENGAGE
BRAKE
LE BRAKE
A BRAKE
INBD BRAKE
MANUAL COMMAND PROGRAM
RATE
SELECT
FAST NORM SLOW
TRIM RESET
ROLL
TRIM
LIGHT TEST
PREFLIGHT TEST
ON
OFF
TRAILING EDGE COMMAND
LEADING EDGE CMD

# OBJECTIVE

VALIDATE DESIGN CONCEPT FOR A VERY LIMITED SET OF TEST CONDITIONS FOR MODES/COMBINATIONS

- MANEUVER CAMBER CONTROL (MCC)
- CRUISE CAMBER CONTROL (CCC)
- MANEUVER LOAD CONTROL (MLC)
    - MCC/MLC
- MANEUVER ENHANCEMENT/GUST ALLEVIATION (MEGA)
    - MEGA/MCC
    - MEGA/MLC
    - MEGA/MCC/MLC

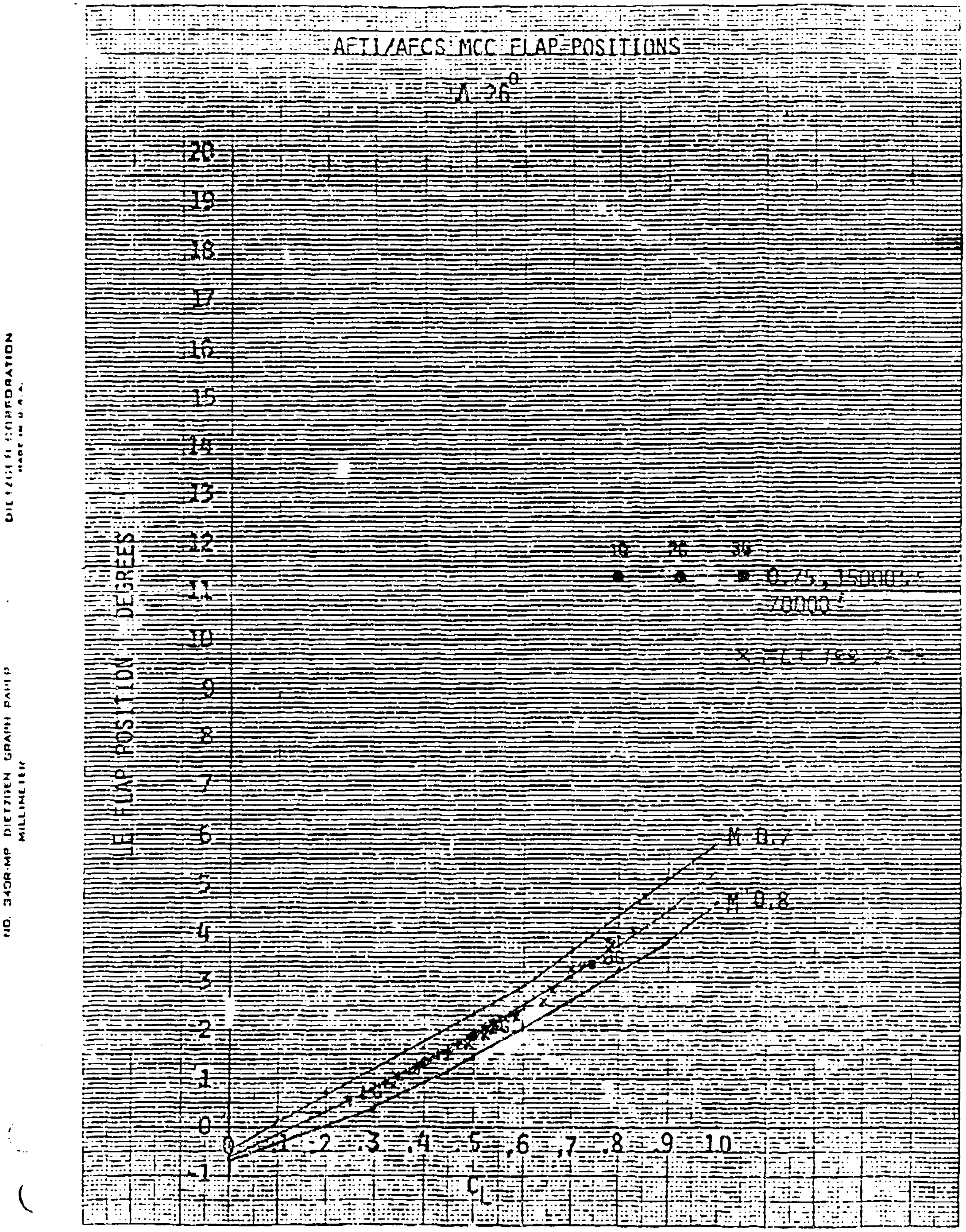
# MCC TESTS

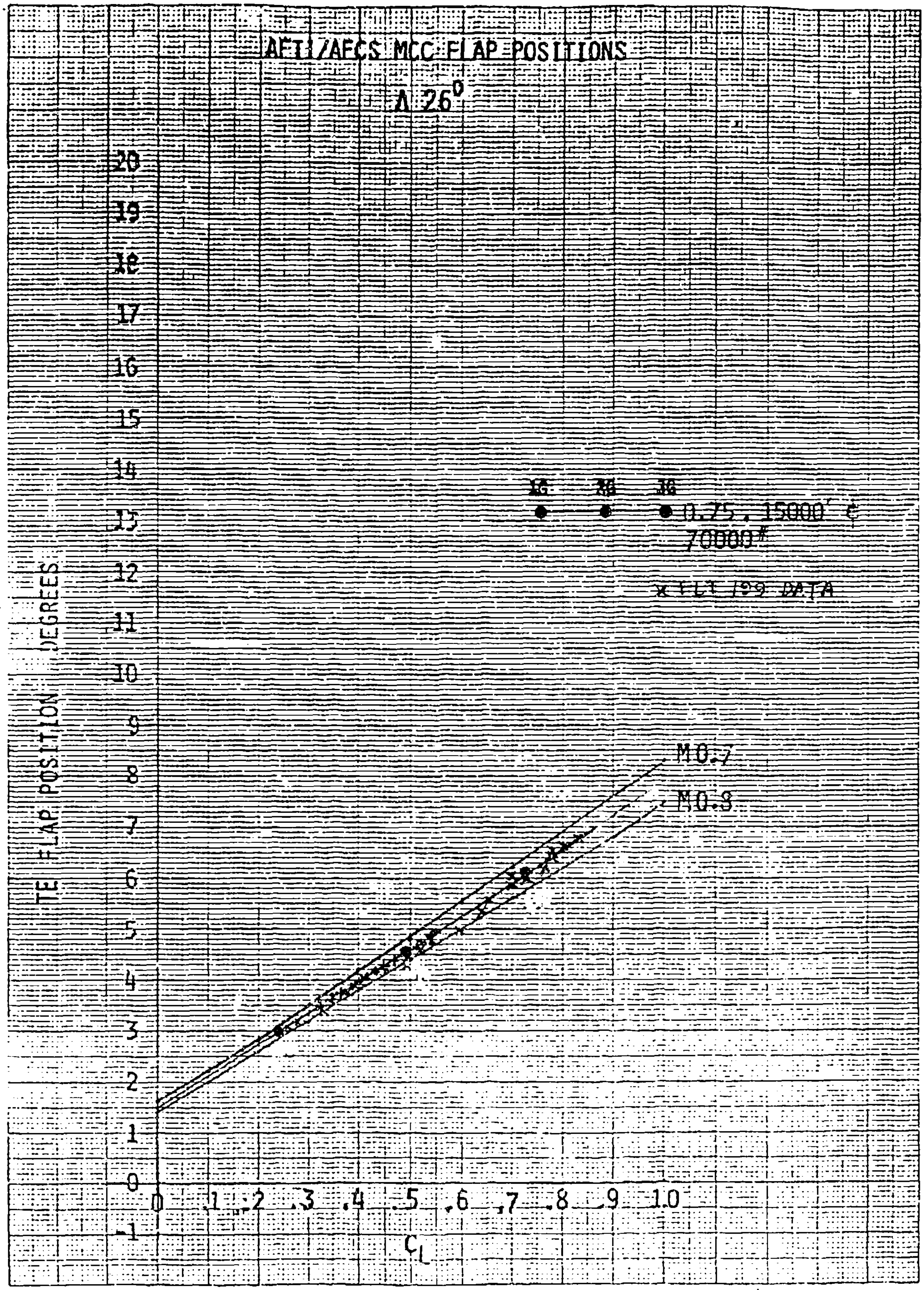
OBJECTIVE: ACCOMPLISH FOLLOWING TESTS

- MANUAL MODE TESTS TO VALIDATE FLAP COMMANDS
- SUBSONIC ENGAGEMENTS AT 26° WING SWEEP
    - ASE (M=0.75, HP=15,000)
    - HANDLING QUALITIES
    - PERFORMANCE TESTS
    - TRACKING TESTS
- SUPERSONIC ENGAGEMENTS
    - ASE (M=1.2, HP=30,000)
    - HANDLING QUALITIES

# MCC PRE-ENGAGEMENT FLIGHT TESTS

- MCC LEADING AND TRAILING EDGE COMMANDS ARE CALCULATED WHENEVER MAW SYSTEM IS ACTIVE
- LIFT COEFFICIENTS AND MCC COMMANDS ARE ON THE PCM DATA STREAM


AFTI/AFCS MCC FLAP POSITIONS
Λ 26°
LE FLAP POSITION DEGREES
M 0.7
M 0.8
$C_L$


AFTI/AFCS MCC FLAP POSITIONS
Λ 26°
TE FLAP POSITION DEGREES
$C_L$
1G 2G 3G
0.75, 15000' & 70000#
x FLT 199 DATA
M0.7
M0.8

## CLEARANCE MANEUVERS MCC

1. <u>1G RAP SET</u>

- TRIMMED LEVEL FLIGHT, ON CONDITION.
- SHARP LATERAL STICK RAP
- SHARP RUDDER KICK
- SHARP NOSEDOWN PITCH RAP

2. <u>HANDLING QUAL EVAL</u>

- BANK, G & ATTITUDE CAPTURES AT DISCRETION OF PILOT.
- LOAD FACTOR WITHIN + .5 TO 1.5G.
- LONGITUDINAL FREQUENCY SWEEP
- PITCH DOUBLET

MACH NO 0.75, ALTITUDE 15000 FT

MACH NO 1.20, ALTITUDE 30000 FT

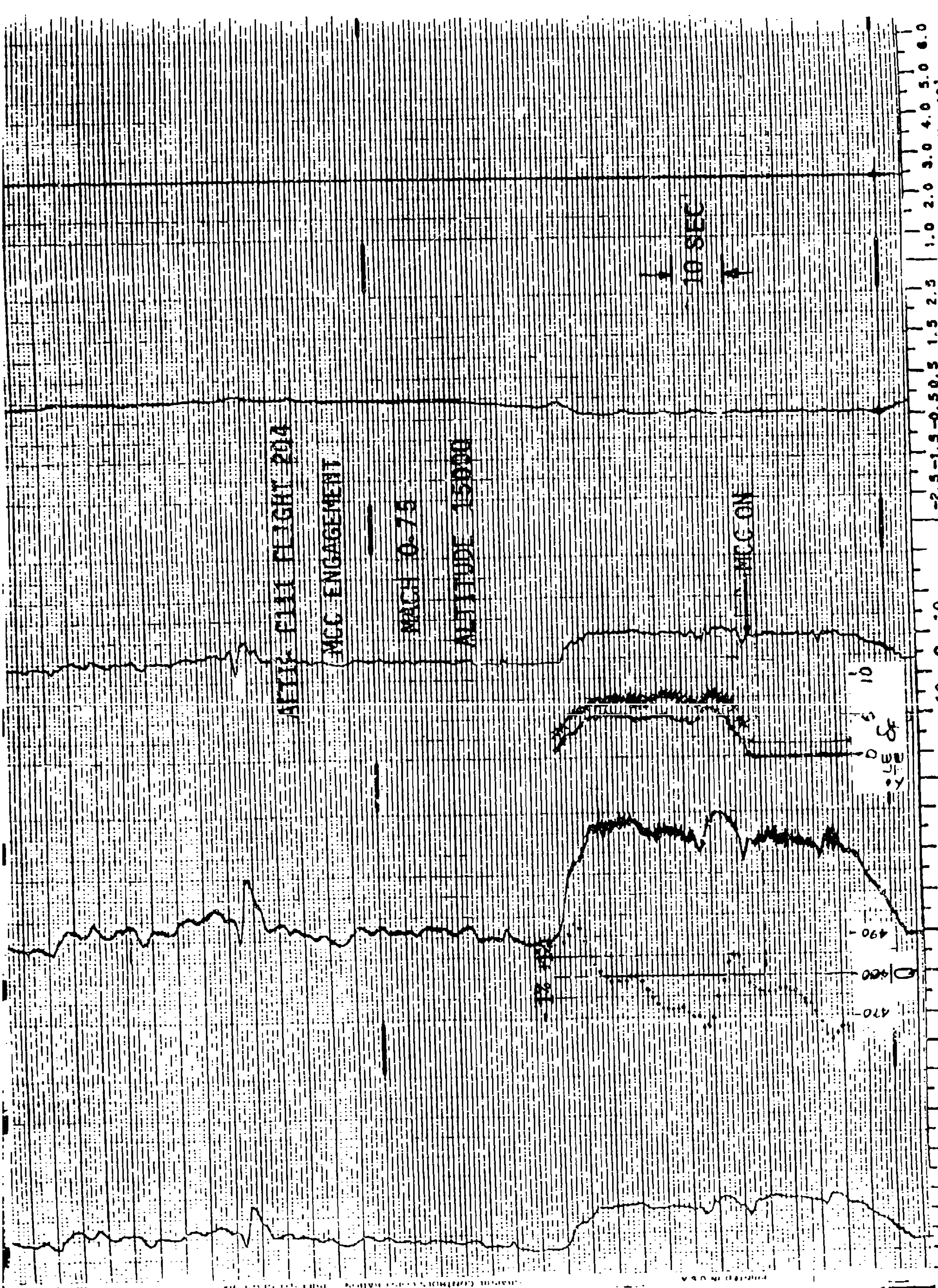
# MCC SUBSONIC ENGAGEMENTS/RESULTS

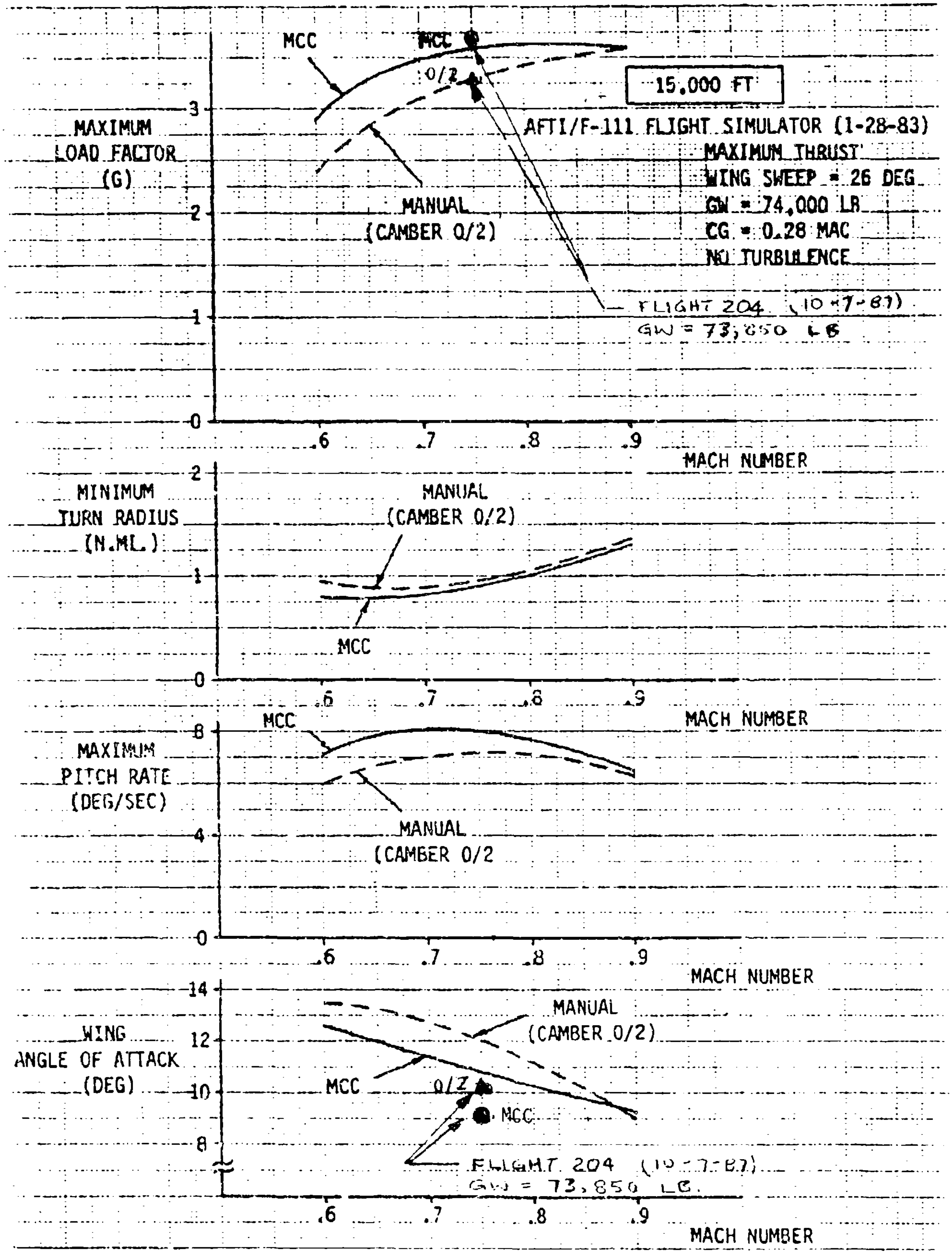
SWEEP 26°

- ASE-ROLL, YAW & PITCH RAPS SATISFACTORY
- PITCH & ROLL ANGLE CAPTURES-PITCH RESPONSE GOOD
- 2 G & 3 G WIND UP TURNS - SATISFACTORY - PILOT COMMENTS
- MANUAL $P_s$ = O TURN ENGAGE MCC
- ENGAGE FROM CCC - SATISFACTORY - GAINED .015 MACH NO.
- MCC TRACKING TESTS - COMMENTS

# MCC SUBSONIC PILOT COMMENTS

- "MCC ENGAGEMENT WAS SMOOTH AT 1 G - NO TRANSIENTS NOTED"
- IN WIND UP TURNS -" A NOTICEABLE IMPROVEMENT IN NOSE TRACKING PERFORMANCE"
- "BUFFET ENCOUNTERED IN MANUAL WAS AVOIDED WITH MCC ENGAGED"
- "TRIM CHANGES WERE MINOR"
- "THE CAMBER CHANGES COULD BE FELT AS SMALL, DISCRETE G CHANGES - THIS WAS NOT OBJECTIONABLE"


AFTI/F-111 FLIGHT 204
MCC ENGAGEMENT
MACH 0.75
ALTITUDE 15000
MCC ON
10 SEC
WING SWEEP POS
DD002
YAW RATE
RAG004
PITCH RATE
RAG001
STRIPCHART NUMBER 2




| CALC | J. HALL | 2-1-83 | REVISED | DATE |
|---|---|---|---|---|
| CHECK | | | | |
| APR | | | | |
| APR | | | | |

EFFECT OF MCC MODE
ON MAXIMUM SUSTAINABLE LEVEL FLIGHT TURN
15,000 FT

FIG 1

THE BOEING COMPANY

PAGE

# MCC SUBSONIC TRACKING TESTS

- HANDLING QUALITIES AS GOOD AS OR BETTER THAN MANUAL MODE
- BUFFET IN MANUAL MODE ELIMINATED OR REDUCED IN MCC

# MCC SUBSONIC CONCLUSIONS

- ASE/FLUTTER CLEARED
- PERFORMANCE IMPROVEMENTS ACHIEVED
  - NEED TO QUANTIFY TURN PERFORMANCE BETTER
- LIGHT BUFFET IN TURNS (0/2) ELIMINATED
- TRIM CHANGES MINOR
- TRACKING AS GOOD OR BETTER THAN MANUAL

# SUPERSONIC ENGAGEMENTS

- MACH 1.2
  - FROM C&D PANEL
  - FROM CCC MODE

PROBLEM:

FIRST ENGAGEMENT FOR ASE OK, BUT NEXT ENGAGEMENT FAILED BECAUSE REASONABLENESS TEST FALSE - DIFFERENCE BETWEEN CADC & FCEU QBAR EXCEEDED TOLERANCE FOR SHORT TIME

SOLUTION: SUBSEQUENT ENGAGEMENTS SATISFACTORY WITH ORIGINAL TOLERANCE

OPEN TOLERANCE-INCORPORATED

# MCC SUPERSONIC CONCLUSIONS

- ENGAGEMENT MARGINAL WITH ORIGINAL QBAR REASONABLENESS TOLERANCE
- ASE/FLUTTER SATISFACTORY AT M= 1.2, 30000 FT
- HANDLINGS QUALITIES SATISFACTORY AT M= 1.2, 30000 FT
- COMPARABLE PERFORMANCE DATA NOT OBTAINED

# CCC TESTS

OBJECTIVE:

(1) TO HAVE CCC DETERMINE OPTIMUM T.E. CAMBER WITH INITIAL FLAP POSITIONS ABOVE AND BELOW EXPECTED OPTIMUM

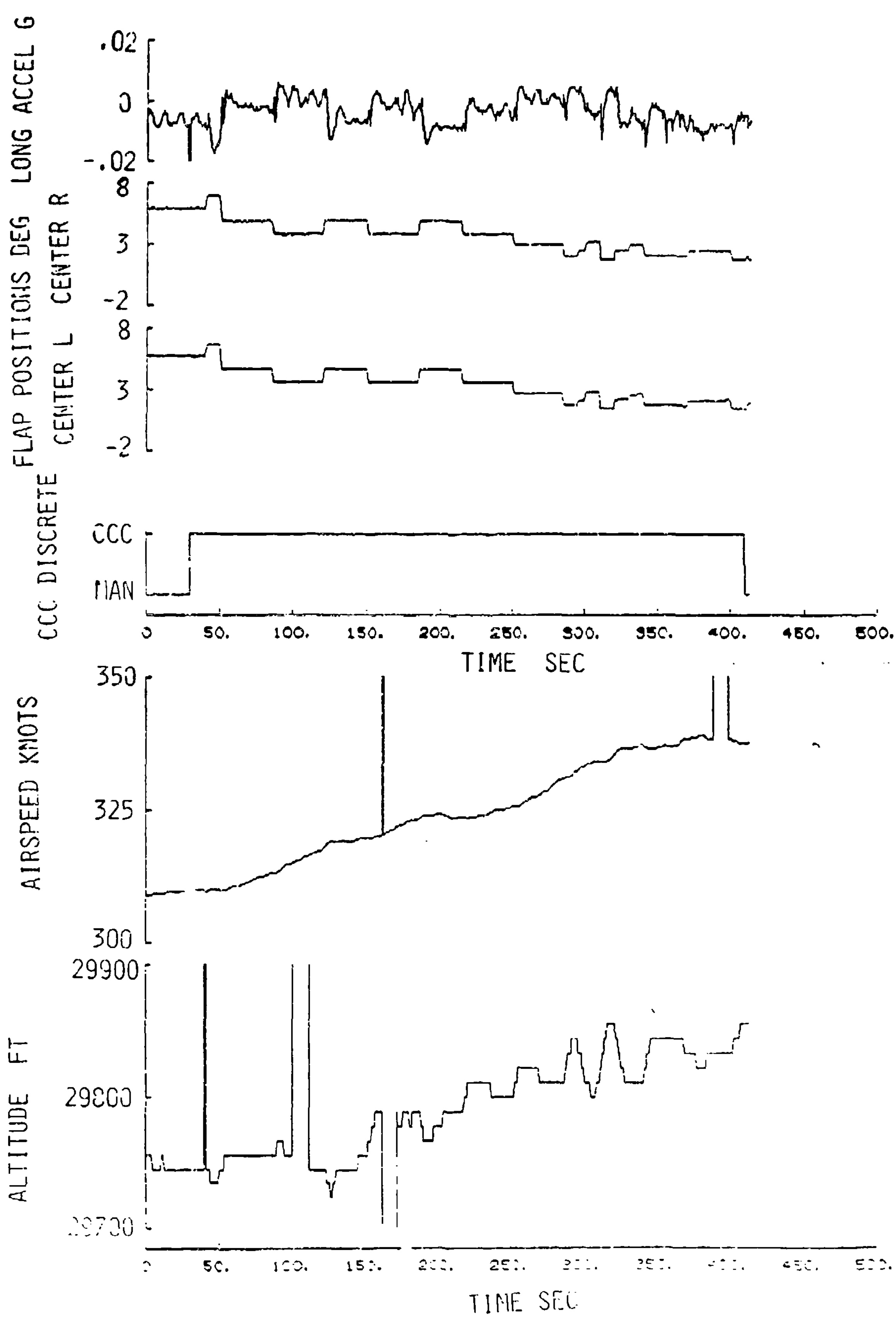
(2) DEMONSTRATE CCC TRANSFER TO MCC WITH BANK ANGLE >30°

- SUBSONIC ENGAGEMENTS 26° SWEEP
- SUBSONIC ENGAGEMENTS 58° SWEEP
- SUPERSONIC ENGAGEMENTS 58°

SUMMARY OF THE CCC MODE RESULTS

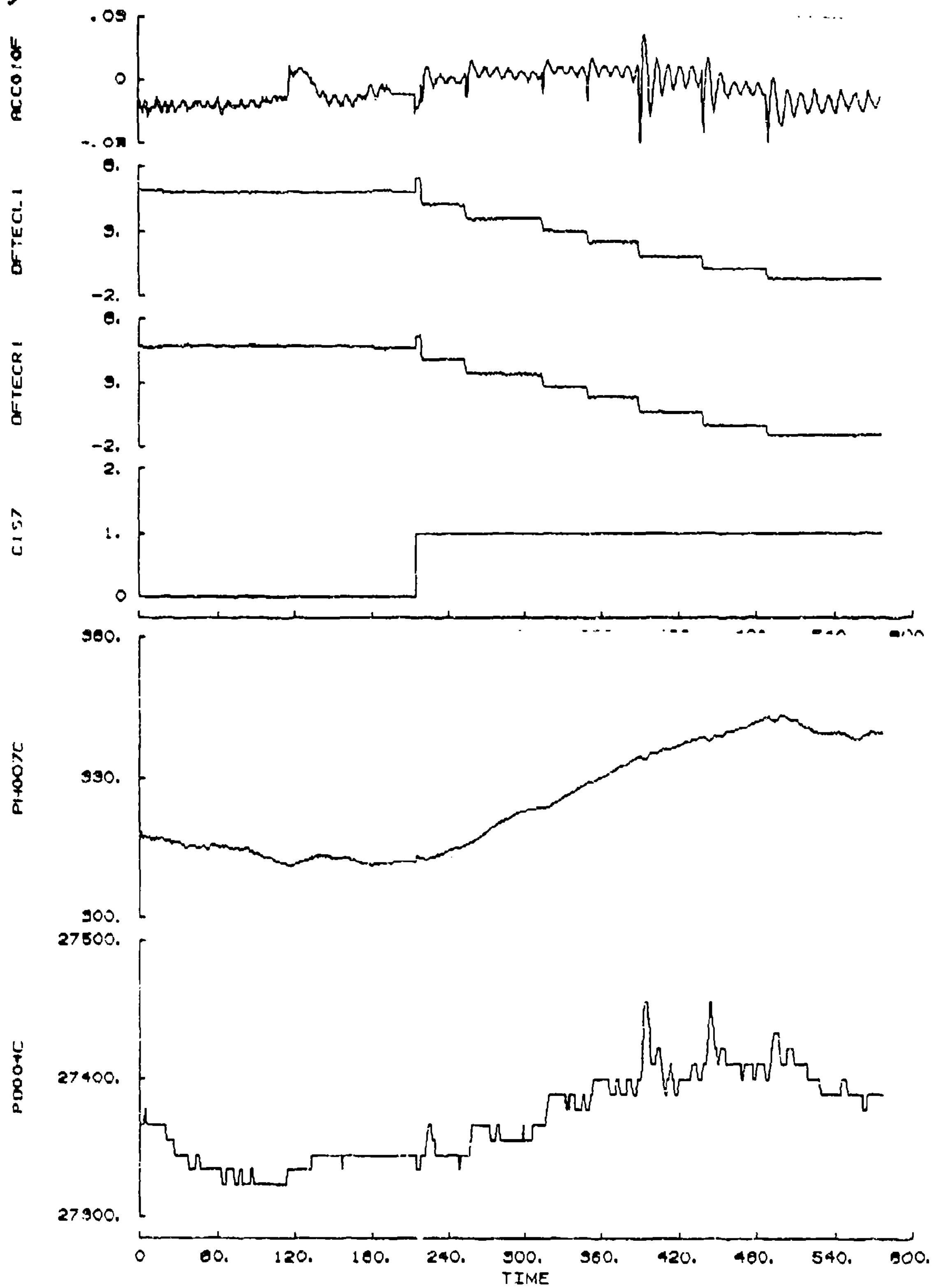
| INITIAL | | | MAXIMUM MACH | | | FINAL CONDITIONS | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| MACH | ALT. | $\delta F$ | MACH | $\delta F$ | TIME | MACH | $\delta F$ | TIME | $\Lambda$ | REMARKS |
| 0.742 | 15130 | 6.0 | .787 | 1.3 | 4:04 | 0.783 | 0.3 | 4:09 | 26 | |
| 0.751 | 15160 | -0.7 | .764 | 0.1 | 3:09 | 0.763 | -0.7 | 3:31 | 26 | FLAPS BRIEFLY MOVED TO .3 THEN RETURNED TO -.7 & STAYED |
| 0.851 | 30380 | -0.7 | FINAL | | | 0.882 | -0.7 | 5:07 | 26 | |
| 0.886 | 30110 | -0.7 | FINAL | | | 0.911 | 0.2 | 2:19 | 58 | STILL SEARCHING |
| 1.202 | 30430 | 2.0 | INITIAL | | | 1.182 | 5.0 | 1:50 | 58 | FLAPS ALWAYS WENT WRONG DIRECTION |
| 0.830 | 30280 | 6.0 | .902 | 2.0 | 5:34 | 0.900 | 1.8 | 6:15 | 26 | MADE SOME MIS-TAKES BUT SPEED INCREASED |
| 0.835 | 30280 | 1.0 | INITIAL | | | 0.771 | -0.7 | 4:15 | 26 | FLAPS WENT TO -0.7 & STAYED |
| 0.810 | 27610 | 4.0 | .818 | 1.0 | 2:00 | 0.776 | -0.7 | 5:24 | 26 | FLAPS ALWAYS WENT HIGHER STAYED FULL UP |
| 0.798 | 27550 | 6.0 | .870 | 0.1 | 4:42 | 0.861 | -0.7 | 6:17 | 26 | SAME AS ABOVE |

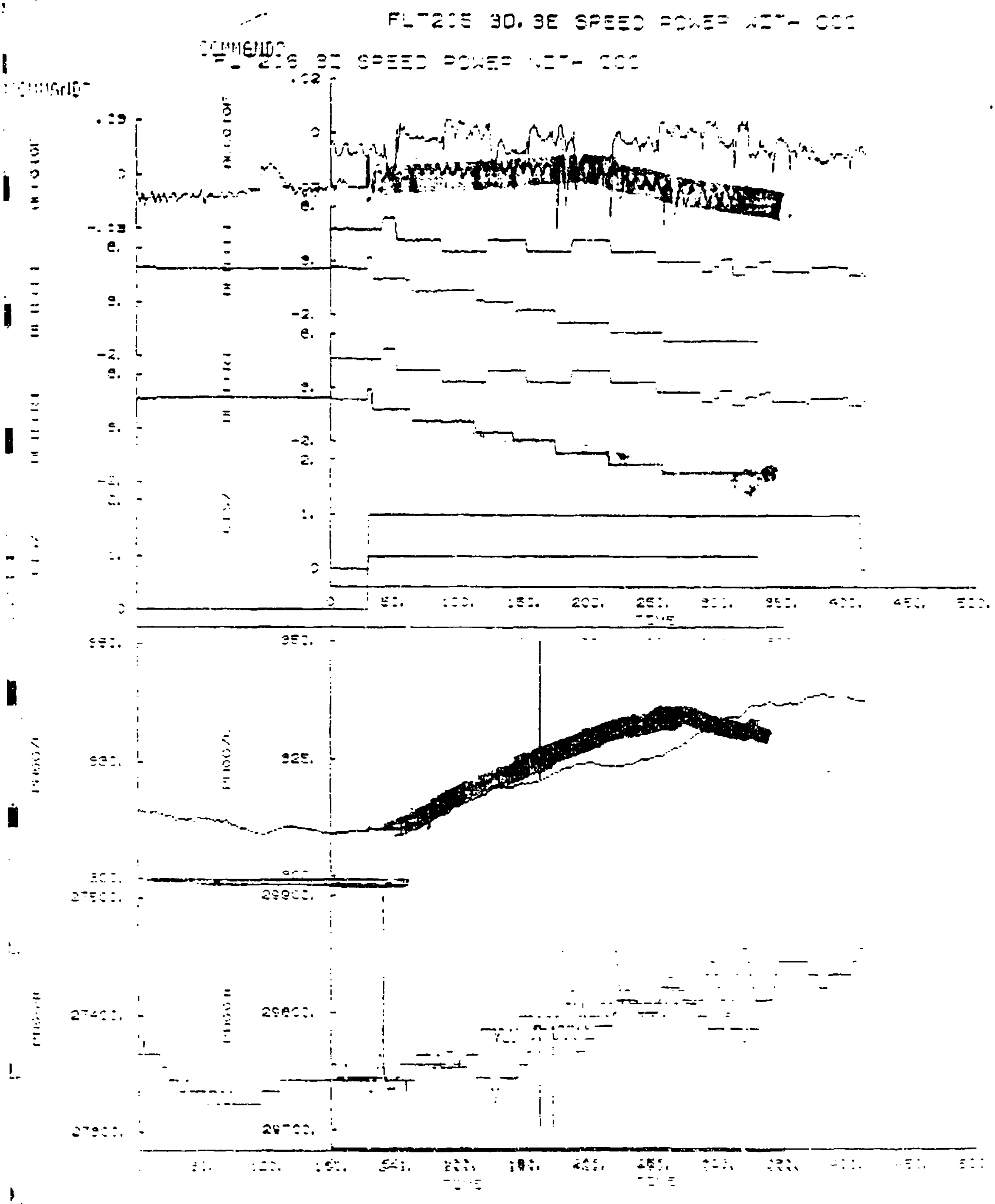
FLT205 30.3E SPEED POWER WITH CCC



FLT206 3I SPEED POWER WITH CCC

COMMAND?




FLT208 30.3E SPEED POWER WITH OCC

# CCC MODE CONCLUSIONS

- CCC MODE DOES NOT OPERATE CONSISTENTLY OR RELIABLY AS CURRENTLY MECHANIZED
- ALGORITHM APPEARS TO OPERATE PER DESIGN
- BODY MOUNTED LONGITUDINAL, ACCELEROMETERS ARE NOT SATISFACTORY AS SENSOR SOURCE
- SOLUTION-CHANGE SENSOR SOURCE AND CHANGE COMMAND LIMITS TO FLAP ELECTRICAL LIMITS
- CCC "DOWNMODED" TO MCC SUCCESSFULLY IN SUBSONIC
- CCC ATTEMPT TO DOWNMODE TO MCC AT MACH 1.2 UNSUCCESSFUL ON ONLY TRY (QBARRE) - WILL TRY AGAIN

# MLC TESTS

OBJECTIVE: (1) DEMONSTRATE MLC OPERATION AT REDUCED THRESHOLD FLAPS 5/10.

(2) DEMONSTRATE MLC/MCL COMBINATION AT REDUCED THRESHOLD.

- MANUAL MODE PRE-ENGAGEMENT FLIGHT TESTS
- CLEARANCE MANEUVERS
- PROBLEM ENCOUNTERED / SOLUTION
- MLC RESULTS WITH REVISED SYSTEM
- MCC/MLC
- COMPARISONS
  - FLIGHT DATA WITH DESIGN
  - FCEU / INSTRUMENTATION BENDING MOMENTS

| BENDING MOMENT THRESHOLDS | |
|---|---|
| BM Threshold Switch Position | Bending Moment Threshold in-lbs |
| 0 BMTH0 | 14.0E6 |
| 1 BMTH1 | 12.0E6 |
| 2 BMTH2 | 10.0E6 |
| 3 BMTH3 | 9.5E6 |
| 4 BMTH4 | 9.0E6 |
| 5 BMTH5 | 8.5E6 |
| 6 BMTH6 | 8.0E6 |
| 7 BMTH7 | 7.5E6 |
| 8 BMTH8 | 7.0E6 |
| 9 BMTH9 | 6.0E6 |
| 10 BMTH10 | 5.0E6 |
| 11 BMTH11 | 4.0E6 |

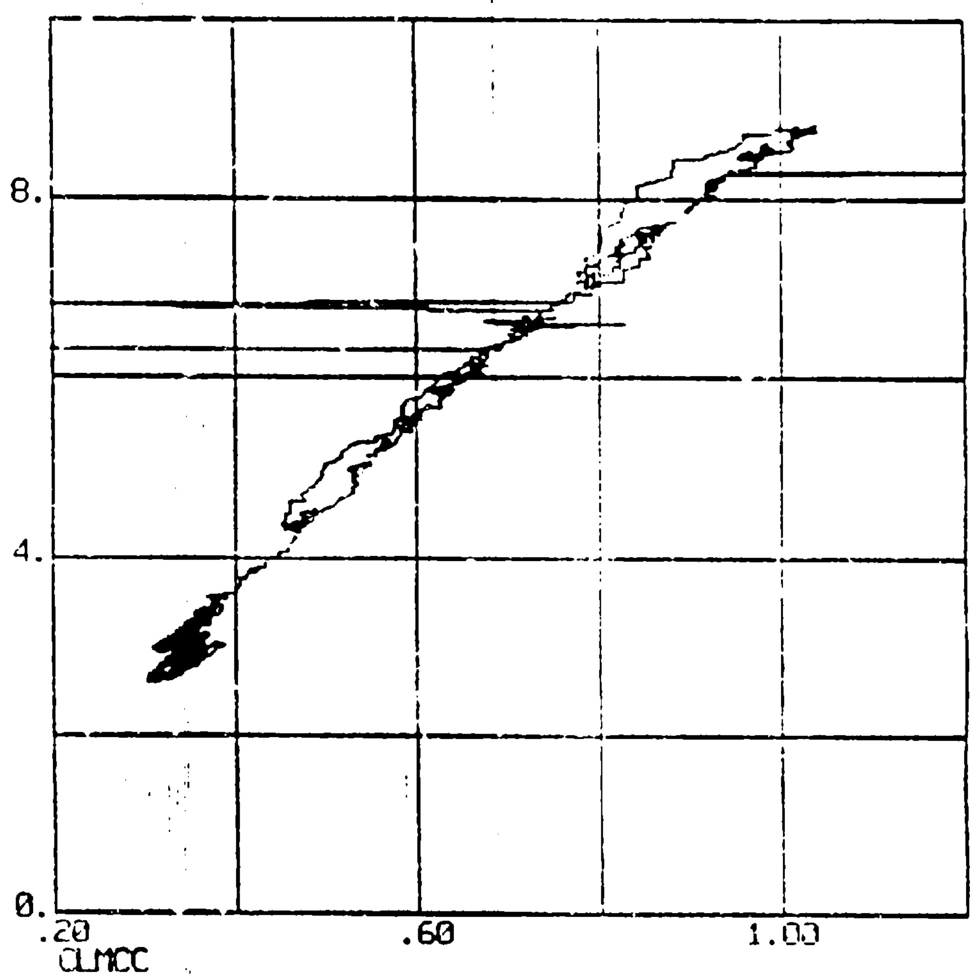
# PRE-ENGAGEMENT FLIGHT TESTS

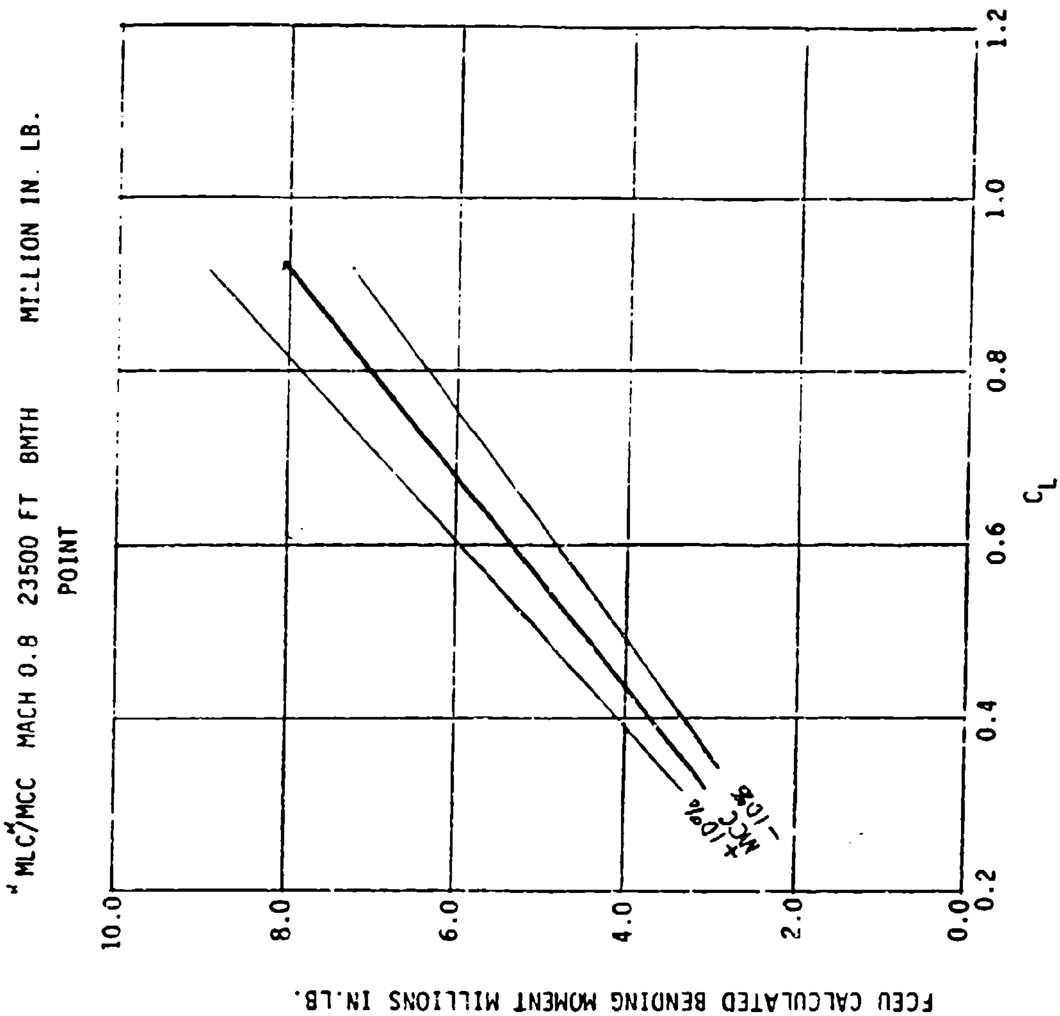
- MLC BENDING MOMENTS CALCULATED WHENEVER MAW SYSTEM IS ACTIVE
- BENDING MOMENTS AND LIFT COEFFICIENTS ARE ON THE PCM DATA STREAM
- MLC DESIGN CHARTS / CONTROL ROOM DISPLAYS AND TOLERANCES

13:56:14.171

13:55:[illegible]

| | |
|---|---|
| CLLE | 1.41 |
| CRLE | 1.41 |
| CLOUT | 4.42 |
| CLMID | 4.42 |
| CLIN | 4.28 |
| CRIN | 4.28 |
| CRMID | 4.14 |
| CROUT | 4.1 |
| FLLE | 1.33 |
| FRLE | 1.46 |
| FLOUT | 4.37 |
| FLMID | 4.41 |
| FLIN | 4.27 |
| FRIN | 4.39 |
| FRMID | 4.11 |
| FROUT | 4.23 |
| MINF | .81 |
| NCHS | 335. |
| HP | 22558. |
| FCF | 10551. |
| FCA | 1433. |
| DELTAF | 6145. |
| GBAR | 400. |
| BMCL | 4.5 |
| CLMCC | .48 |
| DCGACL1 | -1.58 |





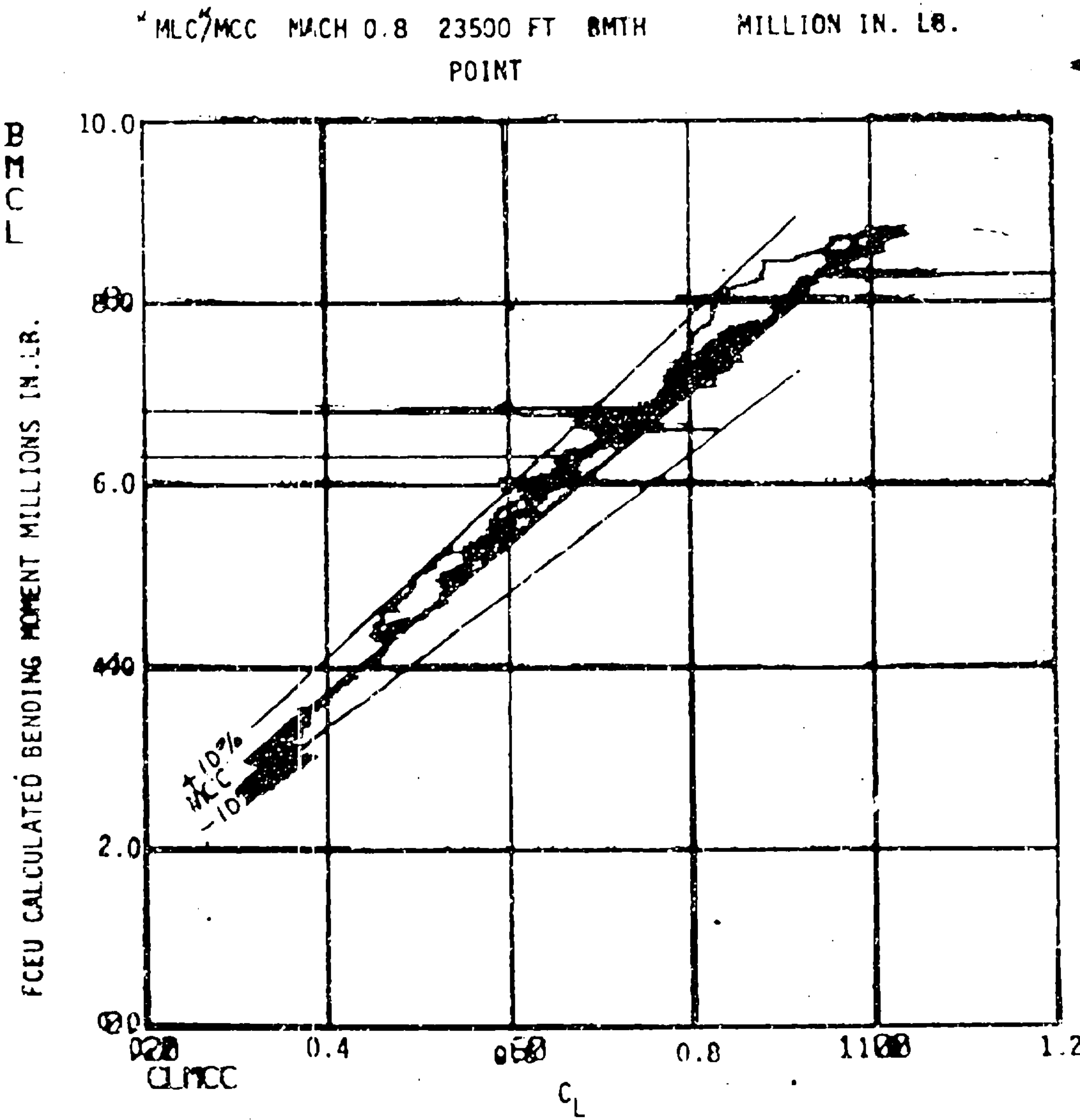

THE BOEING COMPANY

5 II

13:56:14.171

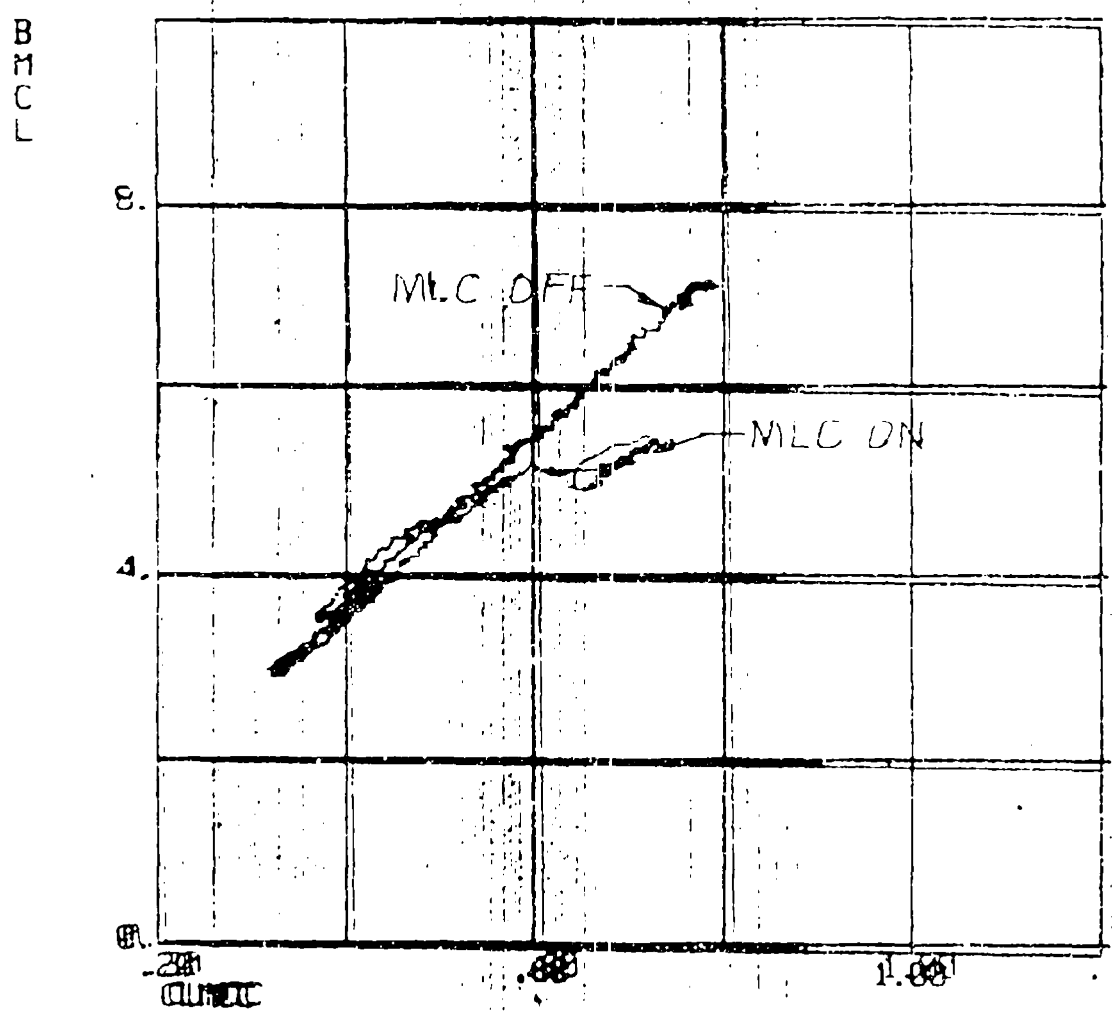
13:59:27.166->

| | |
|---|---|
| CLLE | 1.41 |
| CRLE | 1.41 |
| CLOUT | 4.42 |
| CLMID | 4.42 |
| CLIN | 4.28 |
| CRIN | 4.28 |
| CRMID | 4.14 |
| CROUT | 4.1 |
| PLLE | 1.33 |
| PRLE | 1.46 |
| PLOUT | 4.27 |
| PLMID | 4.41 |
| PLIN | 4.27 |
| PRIN | 4.39 |
| PRMID | 4.11 |
| PROUT | 4.23 |
| MINF | .81 |
| KCAS | 359. |
| HP | 22596. |
| FQF | 10551. |
| FQA | 2402. |
| DELTAF | 8148. |
| QBAR | 400. |
| BMCL | 4.5 |
| CLMCC | .48 |
| ZCGACL1 | -1.58 |



19:07:33.620
19:03:32.620+00

| | |
|---|---|
| CLLE | 2.87 |
| CRLE | 2.80 |
| CLOUT | 5.70 |
| CLMID | 5.88 |
| CLIN | 6.53 |
| CRIN | 6.54 |
| CRMID | 6.20 |
| CROUT | 6.2 |
| PLLE | 2.96 |
| PRLE | 3.00 |
| PLOUT | 5.73 |
| PLMID | 6.83 |
| PLIN | 6.08 |
| PRIN | 6.53 |
| PRMID | 6.19 |
| PROUT | 6.29 |
| MDIF | .81 |
| KCAS | 304. |
| HP | 23854. |
| FQF | 19395. |
| FQA | 2756. |
| DELTAF | 8262. |
| | |
| ODBAR | 365. |
| BMCL | 7.0 |
| CLMCC | .7C |
| ZOOMCL | -2.45 |



# CLEARANCE MANEUVERS MLC

1. <u>1G RAP SET</u>

   - TRIMMED LEVEL FLIGHT, ON CONDITION.
   - SHARP LATERAL STICK RAP
   - SHARP RUDDER KICK
   - SHARP NOSEDOWN PITCH RAP

2. <u>HANDLING QUAL EVAL</u>

   - BANK, G & ALTITUDE CAPTURES AT DISCRETION OF PILOT.
   - LOAD FACTOR WITHIN + .5 TO 1.5G.
   - LONGITUDINAL FREQUENCY SWEEP
   - PITCH DOUBLET

3. <u>X G MLC SWEEP + RAP</u>

   - MLC THRESHOLD SET FOR MLC TRIGGER AT X - .5G
   - ESTABLISH SLOWLY INCREASING WUT UNTIL MLC TRIGGERS
   - SHARP NOSE UP PITCH RAP
   - LOAD FACTOR TO REMAIN <X (X=2,3)

MACH NO 0.80, ALTITUDE 23500 FT $\delta_F$ 5/10

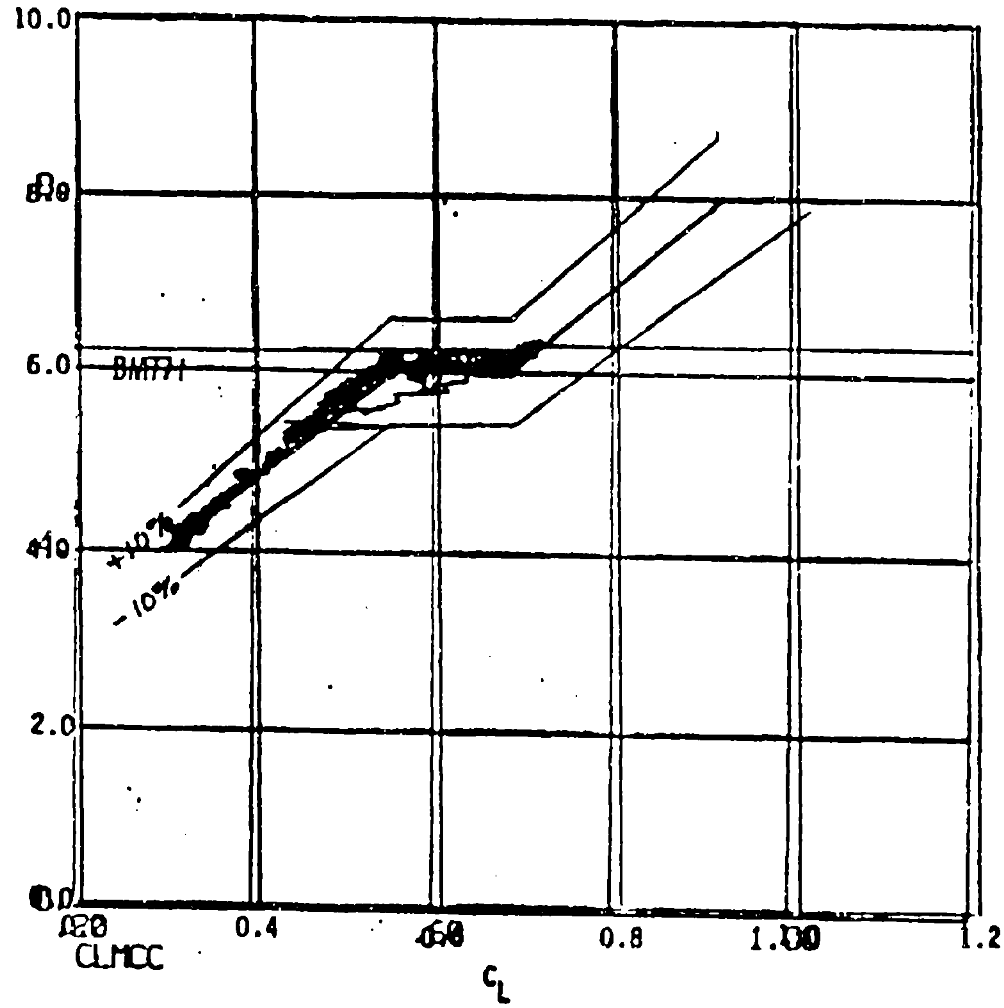
MACH NO 0.80 ALTITUDE 23500 FT $\delta_F$ MCC

MLC MACH 0.8 23500 FT BMTH 6 MILLION IN. LB.

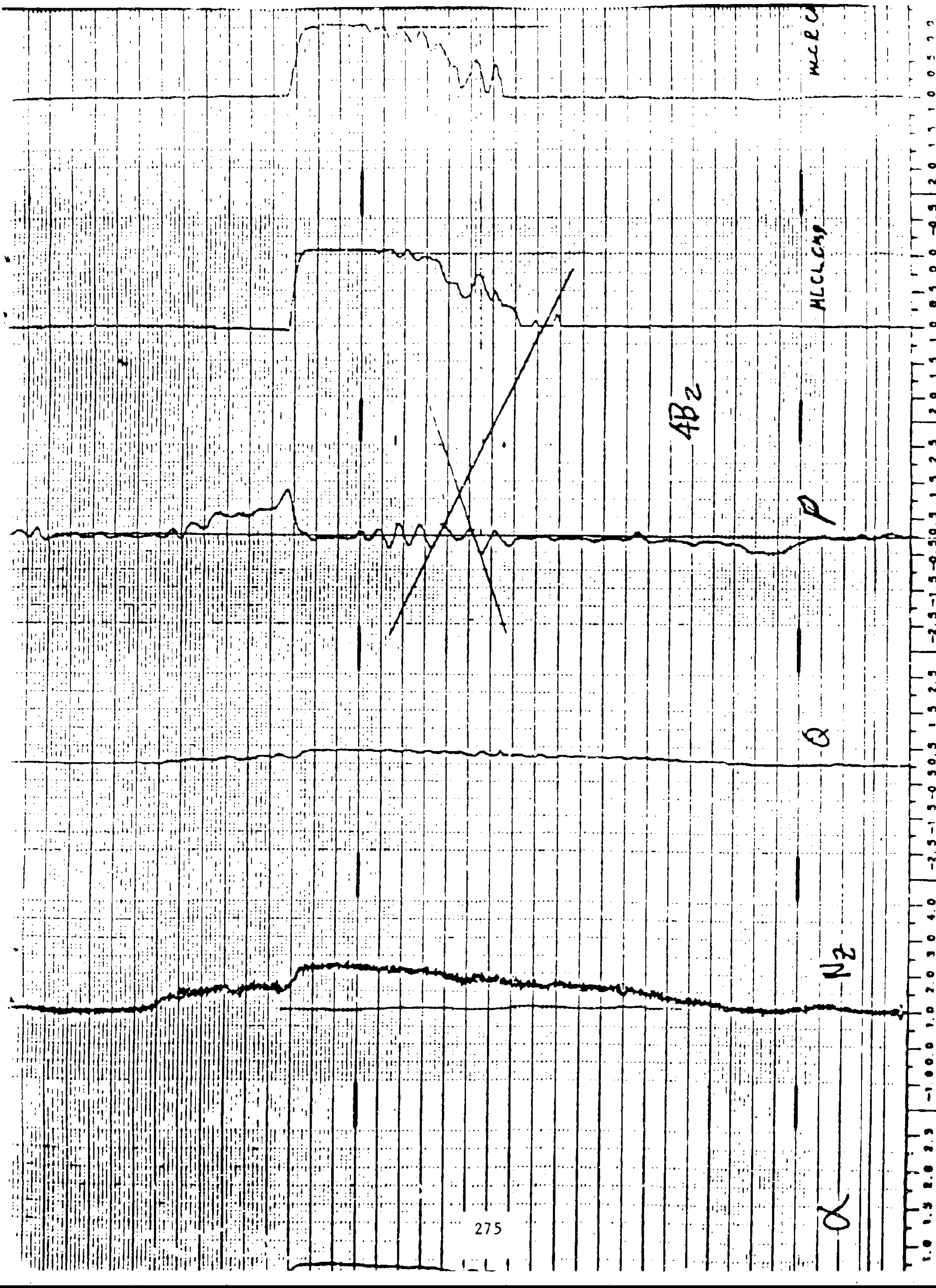
FLT 208 POINT 4B2

| | |
|---|---|
| 13:50:52.136 | |
| 13:51:57.902-> | |
| [illegible]LE | 5.00 |
| [illegible]LE | 5.00 |
| [illegible]OUT | 10.33 |
| [illegible]MID | 10.33 |
| CLIN | 10.00 |
| CRIN | 10.00 |
| CRMID | 9.66 |
| CROUT | 9.6 |
| [illegible]LE | 4.67 |
| [illegible] | 4.68 |
| FLOUT | 10.13 |
| FLMID | 10.38 |
| FLIN | 9.87 |
| FRIN | 9.89 |
| FRMID | 9.70 |
| FROUT | 9.95 |
| [illegible]F | .81 |
| [illegible]S | 358. |
| [illegible] | 22759. |
| [illegible] | 11029. |
| [illegible] | 3148. |
| [illegible]TAF | 7921. |
| [illegible]R | 396. |
| [illegible]L | 5.6 |
| [illegible]CC | .47 |
| [illegible]CL1 | -1.52 |

OVERLAY FOR POINT 4B




482


MCLCMD
ΔBz
P
Q
Nz
α
DEC
MCL CMD
ROLL RATE
DEC/SEC
PITCH RATE
NZ CG
G

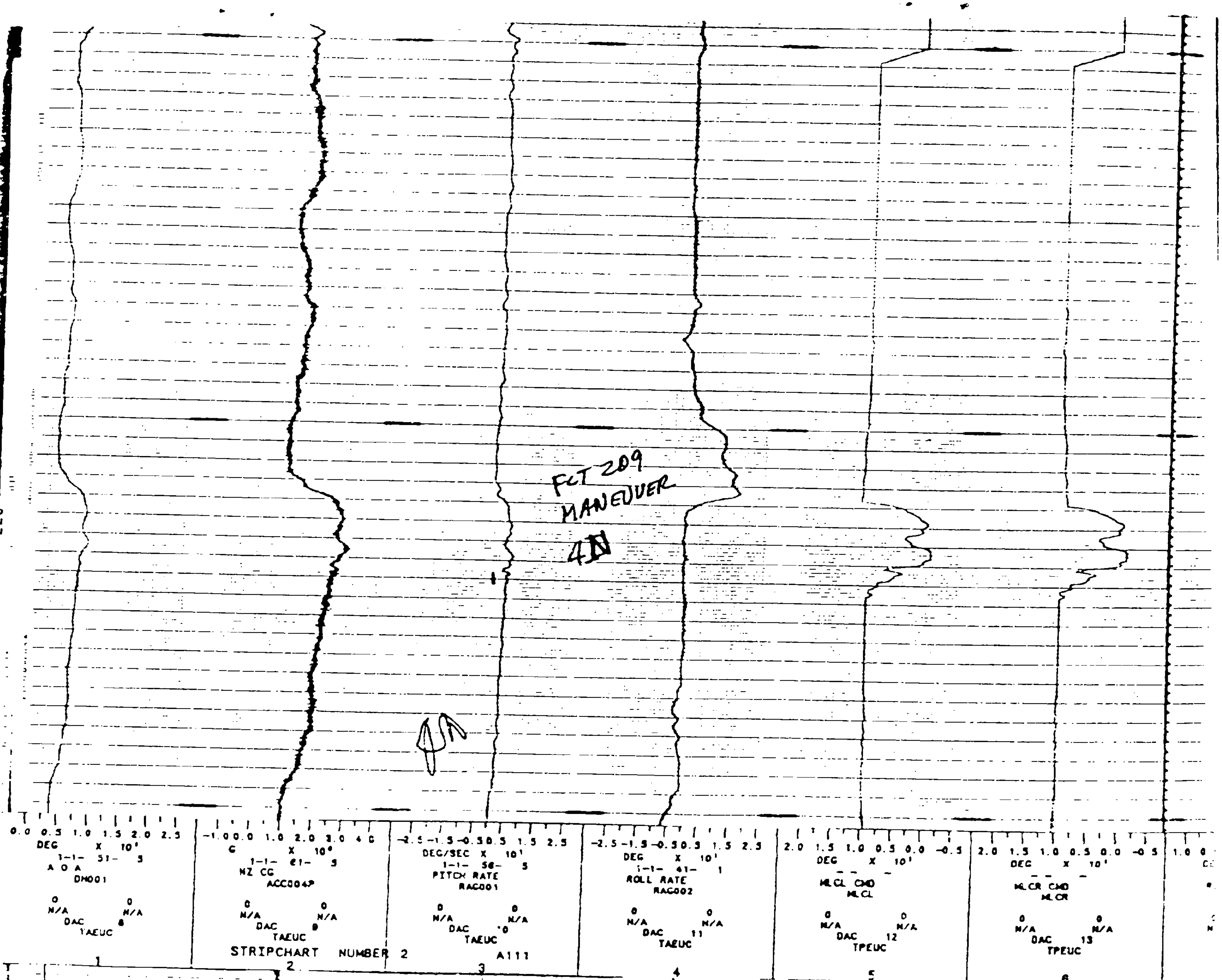
# MLC PROBLEM / SOLUTION

## PROBLEM:

- ROLL PIO DURING MLC FLAP EXCURISION
  - ASYMMETRIC MOTION OF OUTBOARD FLAPS
  - OUTBOARD FLAPS ARE ALSO AILERONS

## SOLUTION:

- PIO CEASES WHEN O/B FLAPS FULL UP
- REMOVE ROLL ACCELERATION AND RATE INPUTS FROM ALGORITHM

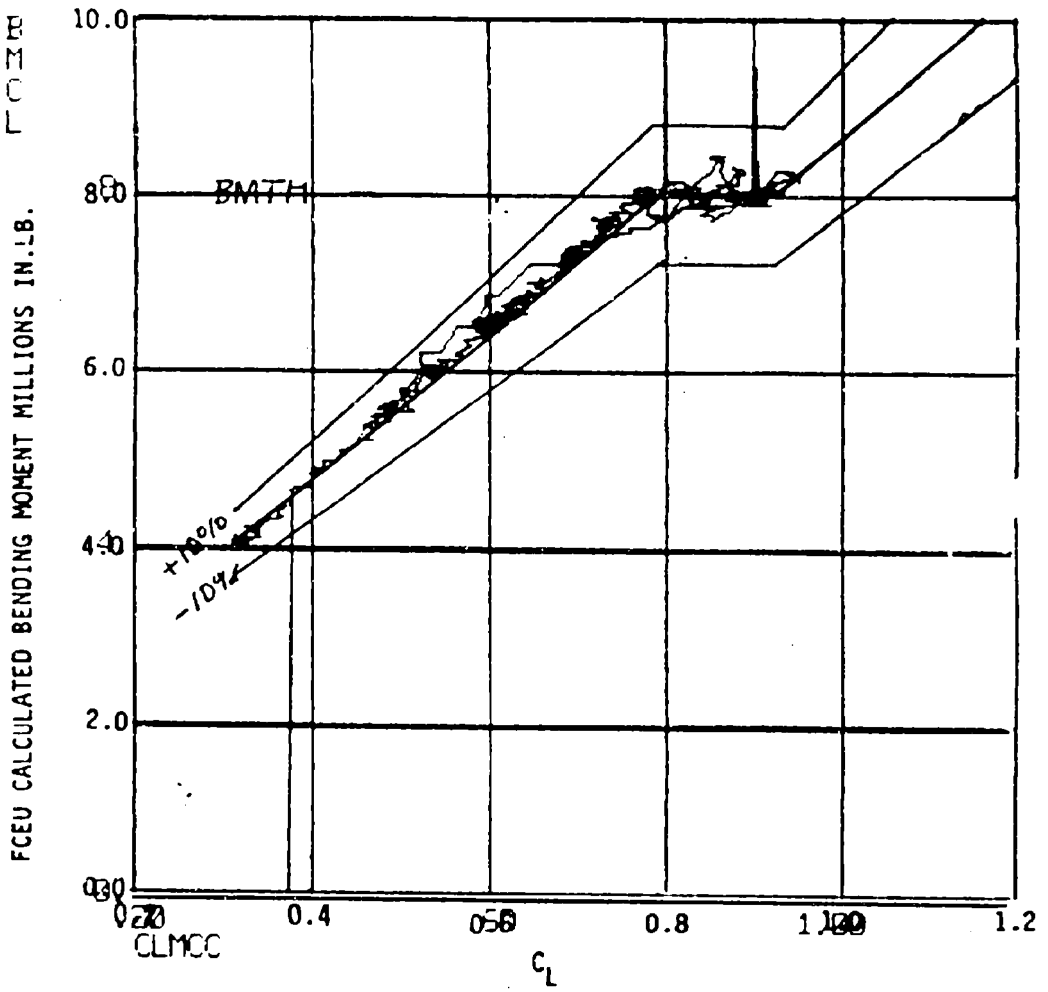

FLT 209
MANEUVER
4B
0.0 0.5 1.0 1.5 2.0 2.5
DEG X 10¹
1-1- 51- 5
A O A
DH001
0 N/A DAC TAEUC 8 0 N/A
1
-1.0 0.0 1.0 2.0 3.0 4.0
G X 10⁰
1-1- 61- 5
NZ CG
ACC004P
0 N/A DAC TAEUC 9 0 N/A
2
-2.5 -1.5 -0.5 0.5 1.5 2.5
DEG/SEC X 10¹
1-1- 56- 5
PITCH RATE
RAC001
0 N/A DAC TAEUC 10 0 N/A
3
-2.5 -1.5 -0.5 0.5 1.5 2.5
DEG X 10¹
1-1- 61- 1
ROLL RATE
RAC002
0 N/A DAC TAEUC 11 0 N/A
4
2.0 1.5 1.0 0.5 0.0 -0.5
DEG X 10¹
MLCL CMD
MLCL
0 N/A DAC TPEUC 12 0 N/A
5
2.0 1.5 1.0 0.5 0.0 -0.5
DEG X 10¹
MLCR CMD
MLCR
0 N/A DAC TPEUC 13 0 N/A
6
STRIPCHART NUMBER 2
A111

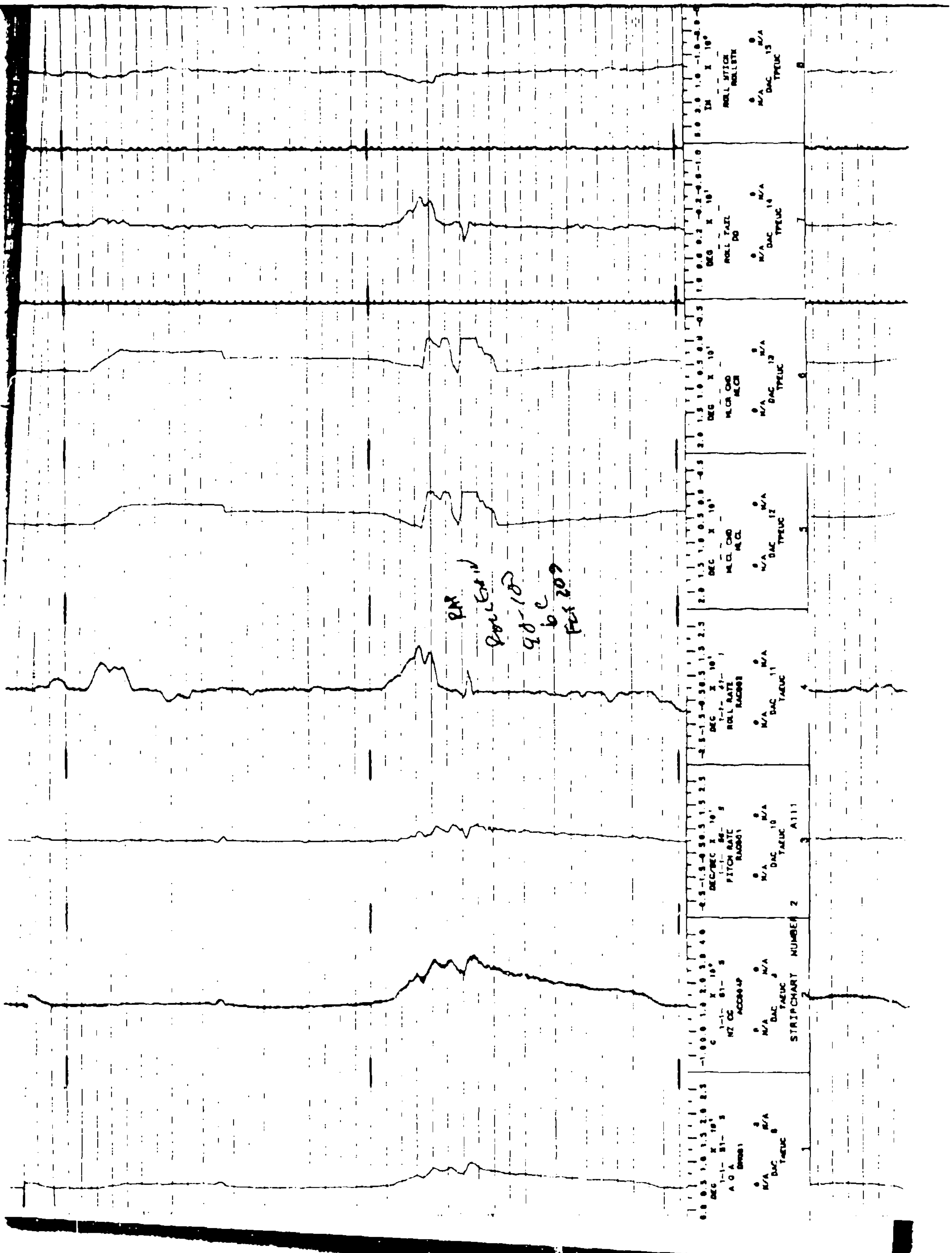
4N

MLC MACH 0.8 23500 FT BMTH 8.0 MILLION IN. LB.
FLT 209 POINT 4N

| | |
|---|---|
| 8:59:45.621 | |
| 9:00:18.220**** | |
| CLLE | 5.00 |
| CRLE | 5.00 |
| CLOUT | 10.77 |
| CLMID | 10.75 |
| CLIN | 10.00 |
| CRIN | 10.00 |
| CRMID | 9.25 |
| CROUT | [illegible] |
| PLLE | 4.73 |
| PRLE | 4.74 |
| PLOUT | 10.51 |
| PLMID | 10.81 |
| PLIN | 9.90 |
| PRIN | 9.94 |
| PRMID | 9.23 |
| PROUT | 9.46 |
| MINF | .81 |
| KCAS | 346. |
| HP | 24549. |
| FQF | 12183. |
| FQA | 3876. |
| DELTAF | 8364. |
| QBAR | 368. |
| BMCL | 5.8 |
| CLMCC | .50 |
| ZCGACL1 | -1.46 |

OVERLAY FOR POINT 4

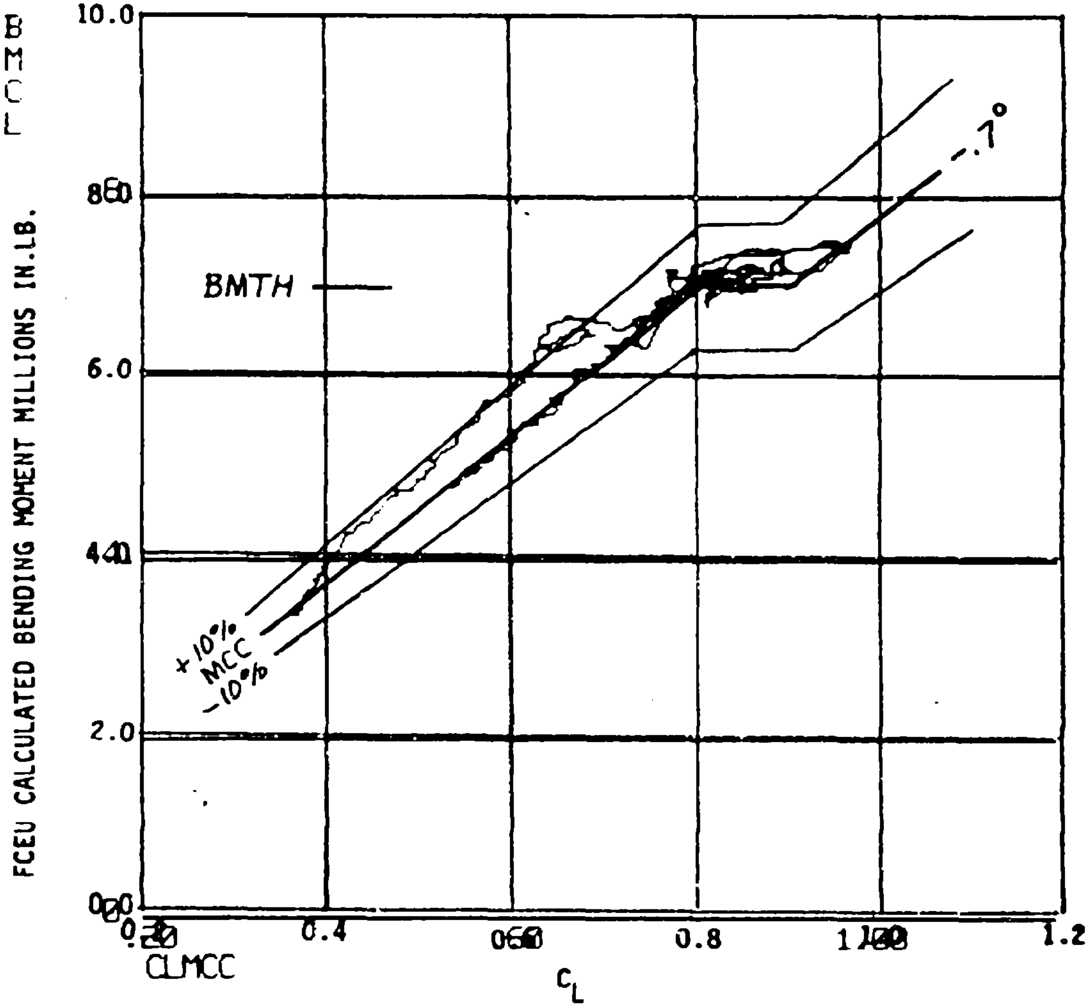


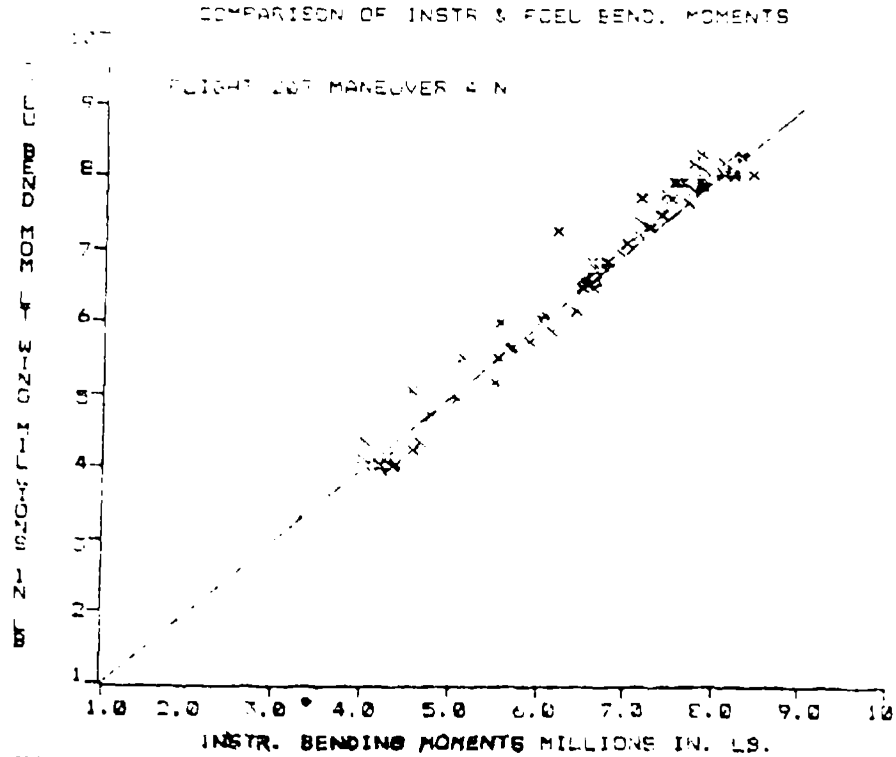

STRIPCHART NUMBER 2
A111
ROLL STICK
ROLL RATE
PITCH RATE
A O A

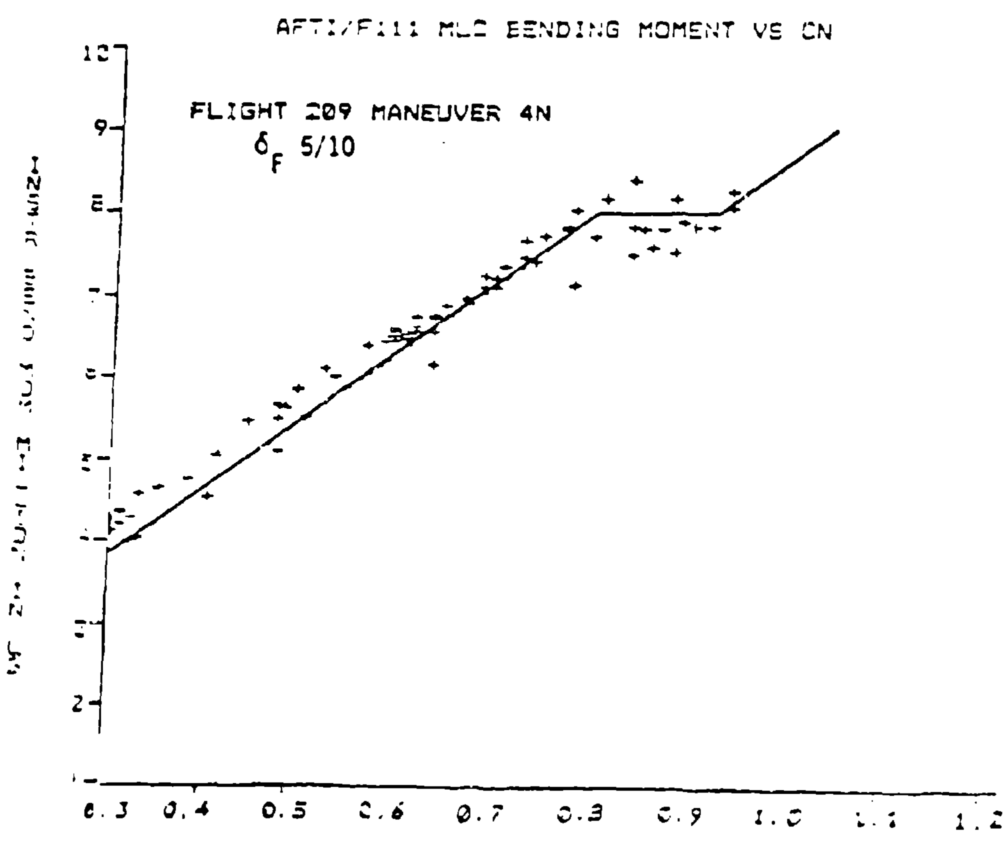
9:06:26.253
9:06:58.352***

| | |
|---|---|
| CLLE | .83 |
| CRLE | .83 |
| CLOUT | 3.63 |
| CLMID | 3.63 |
| CLIN | 3.63 |
| CRIN | 3.63 |
| CRMID | 3.66 |
| CROUT | 3.7 |
| PLLE | .70 |
| PRLE | .75 |
| PLOUT | 3.36 |
| PLMID | 3.58 |
| PLIN | 3.55 |
| PRIN | 3.68 |
| PRMID | 3.55 |
| PROUT | 3.59 |
| MINF | .82 |
| KCAS | 358. |
| HP | 23164. |
| FQF | 11547. |
| FGA | 3557. |
| DELTAF | 7973. |
| QBAR | 396. |
| BMCL | 3.4 |
| CLMCC | .37 |
| ZCGACL1 | -1.17 |

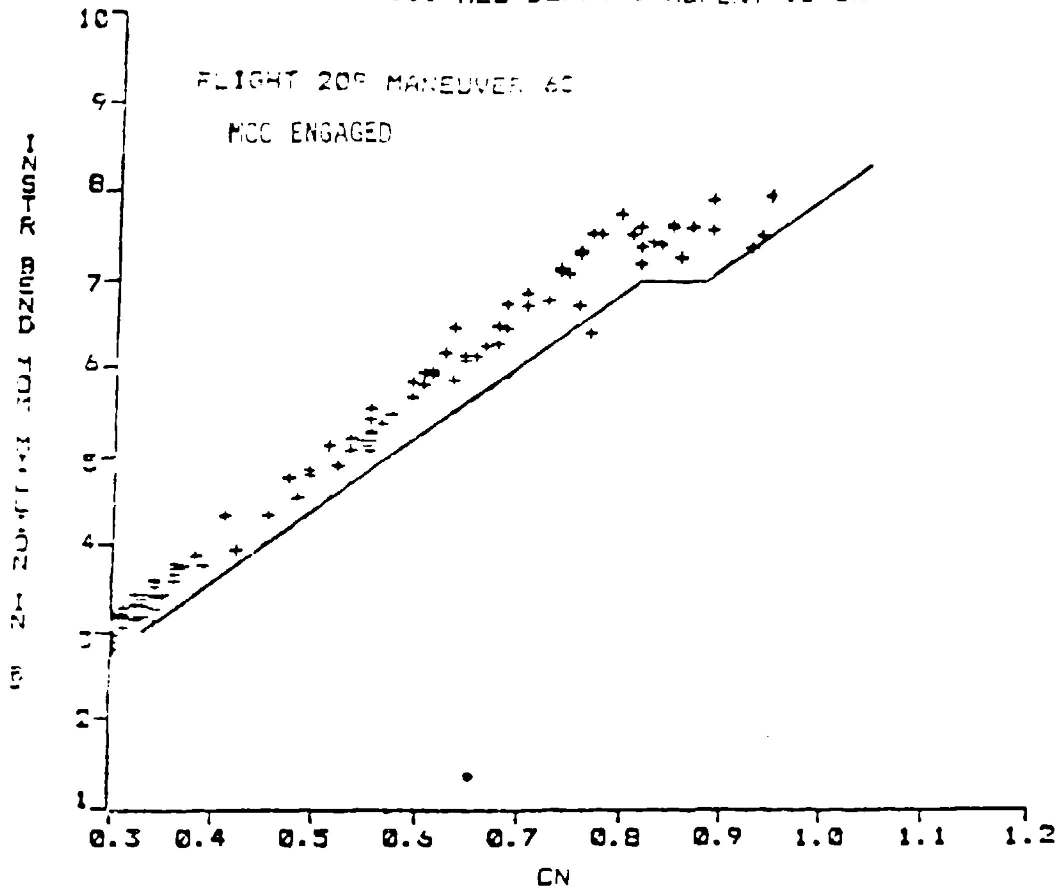
MLC/MCC MACH 0.8 23500 FT BMTH 7 MILLION IN. LB.
PLT 209 POINT 6C



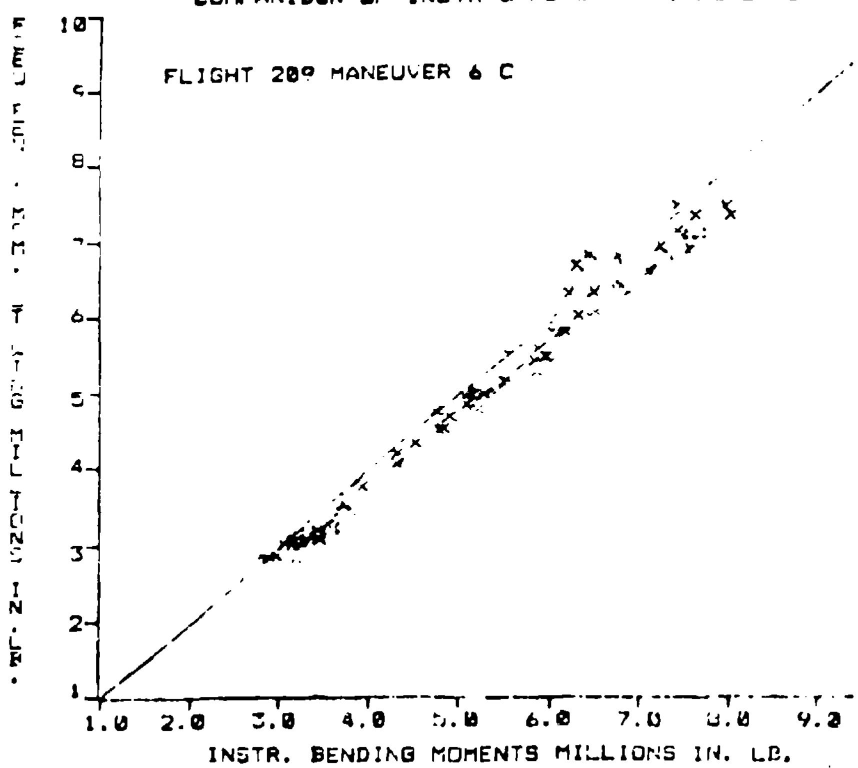

COMPARISON OF INSTR & FCEL BEND. MOMENTS
FLIGHT 207 MANEUVER 4 N
1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0 9.0 10
INSTR. BENDING MOMENTS MILLIONS IN. LB.
1 2 3 4 5 6 7 8 9


AFTI/F111 MLC BENDING MOMENT VS CN
FLIGHT 209 MANEUVER 4N
$\delta_F$ 5/10
0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2
CN
2 8 9 10

AFTI/F111 MLC BENDING MOMENT VS CN




COMPARISON OF INSTR & FCEU BEND. MOMENTS



# MLC CONCLUSIONS

- ASYMMETRIC OUTBOARD FLAP DEFLECTIONS DURING MLC CAN LEAD TO A ROLL PIO
- REMOVING ROLL RATE AND ROLL ACCELERATION INPUTS STOPPED THE ROLL PIO
- MLC MODE OPERATES PER DESIGN PARAMETERS
- MLC/MCC ACTUAL BENDING MOMENTS AT "LOW" TE DEFLECTIONS HIGHER THAN MODE CALCULATIONS DUE TO HIGHER FLAP EFFECTIVENESS AT LOW T.E. DEFLECTIONS

# MEGA TESTS

OBJECTIVES

(1) MANEUVER ENHANCEMENT

- CLEARANCE MANEUVERS
- TRACKING TESTS

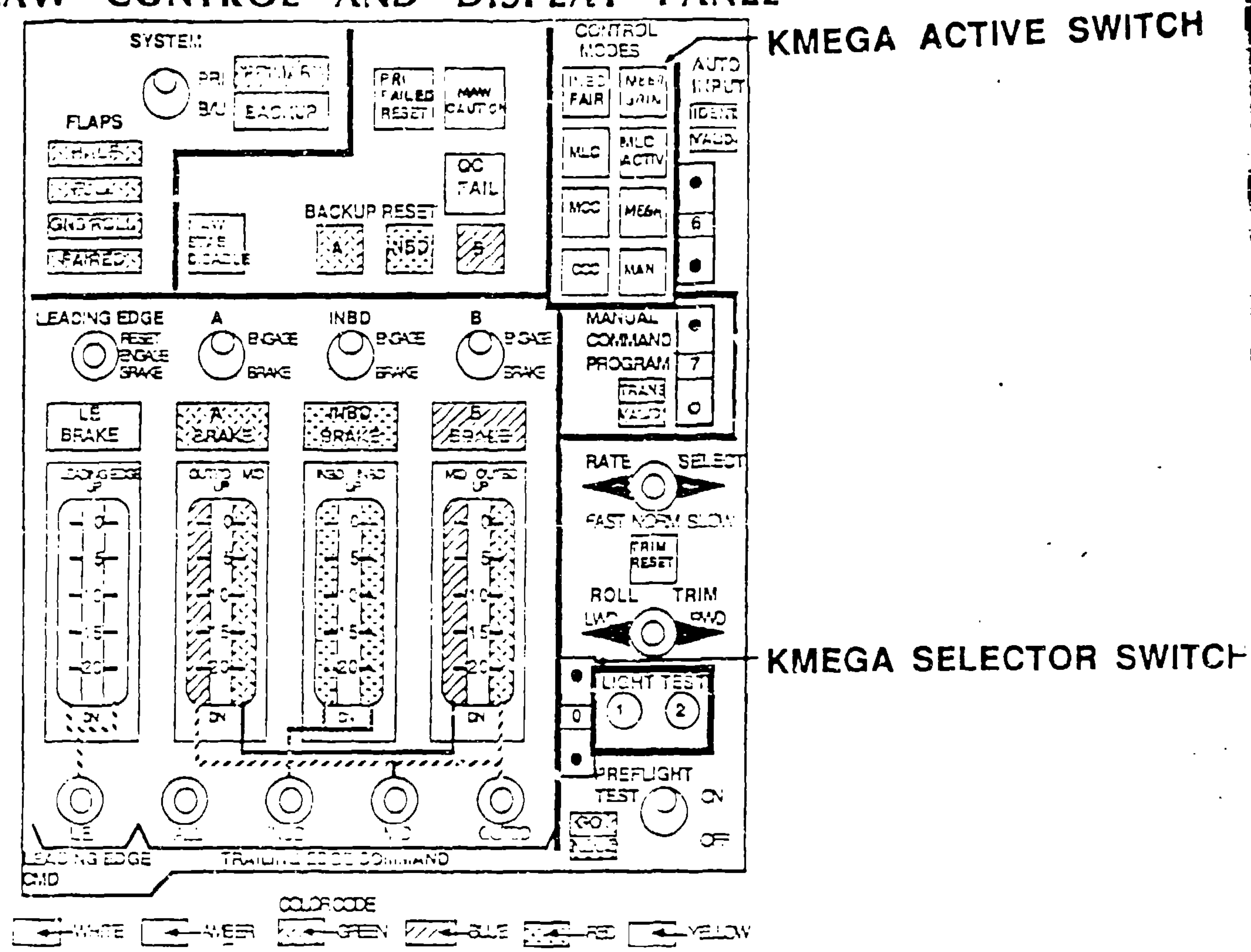
(2) MEGA/MCC

- CLEARANCE MANEUVERS
- TRACKING TESTS

(3) GUST ALLEVIATION

- RIDE QUALITY - MEGA ON VS MEGA OFF

# MAW CONTROL AND DISPLAY PANEL



## CLEARANCE MANEUVERS MEGA

1. 1G RAP SET

   - TRIMMED LEVEL FLIGHT, ON CONDITION.
   - SHARP LATERAL STICK RAP
   - SHARP RUDDER KICK
   - SHARP NOSEDOWN PITCH RAP

2. HANDLING QUAL EVAL

   - BANK, G & ALTITUDE CAPTURES AT DISCRETION OF PILOT.
   - LOAD FACTOR WITHIN + .5 TO 1.5G.
   - LONGITUDINAL FREQUENCY SWEEP
   - PITCH DOUBLET

3. X G MEGA STEP + RAP

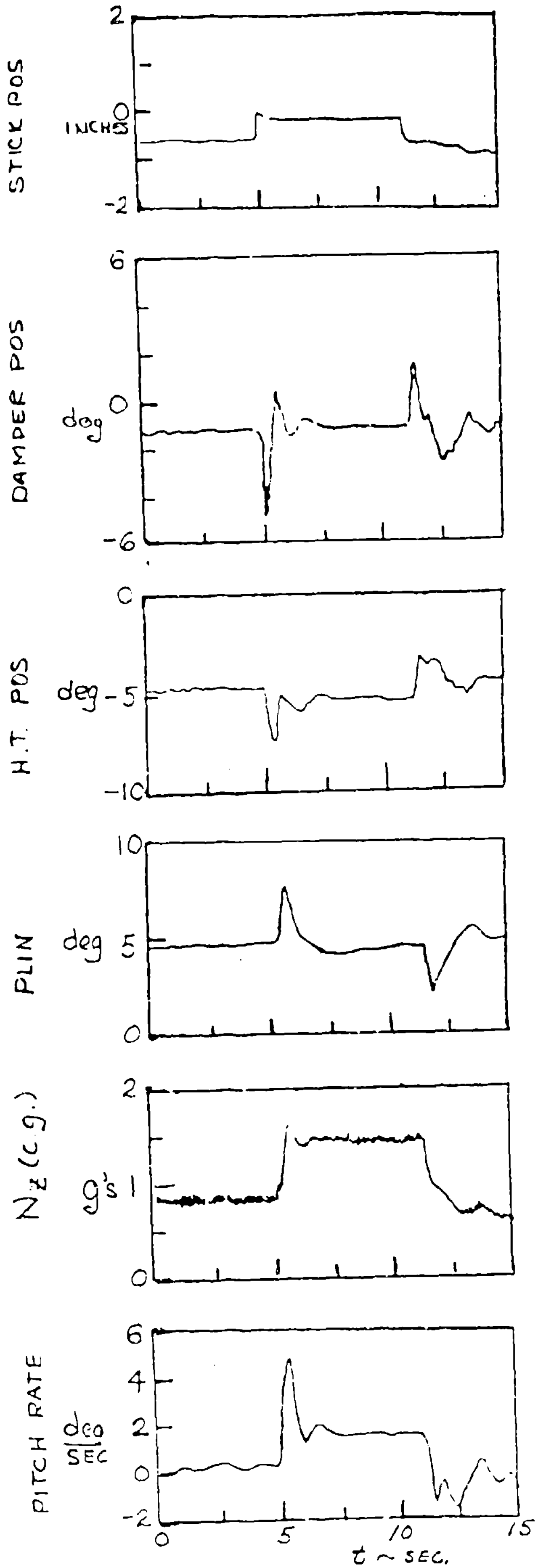
   - ESTABLISH STABILIZED TURN AT X - .5 G, HOLD FOR ~ 5 SEC.
   - MAKE MODERATELY SHARP INPUT, CAPTURE X G LOAD FACTOR
   - HOLD X G
   - SHARP NOSE DOWN PITCH RAP

MACH NO 0.80, ALTITUDE 23500 FT $\delta_F$ 5/6

# MEGA TEST RESULTS

MEGA FLAPS 5/6

- FIRST ENGAGEMENT - FIRST PROBLEM/SOLUTION
- CLEARANCE MANEUVERS
  - 80% GAIN - ALL TESTS ACCOMPLISHED
  - 90% AND 100% GAIN
  - IN ASE - PITCH COUPLES WITH FIRST FUSELAGE BENDING MODE AT NATURAL FREQUENCY OF 4.5 HZ. PILOT AWARE OF COUPLING
- PILOT COMMENTS
  - "WELL DAMPED WITH A NICE CRISP INITIAL RESPONSE THAT WAS EASILY CONTROLLED"
  - "HANDLING QUALITIES WERE NORMAL WITH NO UNCOMMANDED RESPONSES NOTED. LOAD FACTOR RESPONSE WITH BACK STICK INPUT WAS FELT TO BE QUICKER AS MEGA GAIN WAS INCREASED."




AFTI/F-111; FLT 037 (ME/GA)

TIME SEG. 9:31:20 → 9:31:35

$M = 0.8$

$h_p = 23.5K$

$\Lambda = 26°$

$K_{ME/GA} = 0.7$; $K_{AD} = 1.5$

A/C RESPONSE FOLLOWING A 1/2" PSTICK STEP INPUT ~ $\Delta N_z(C.G.) = 0.5$ g's

FLAPS 5/6

## CLEARANCE MANEUVERS MEGA /MCC

1. <u>1G RAP SET</u>

- TRIMMED LEVEL FLIGHT, ON CONDITION.
- SHARP LATERAL STICK RAP
- SHARP RUDDER KICK
- SHARP NOSE DOWN PITCH RAP

2. <u>HANDLING QUAL EVAL</u>

- BANK, G & ATTITUDE CAPTURES AT DISCRETION OF PILOT.
- LOAD FACTOR WITHIN + .5 TO 1.5G.
- LONGITUDINAL FREQUENCY SWEEP
- PITCH DOUBLET

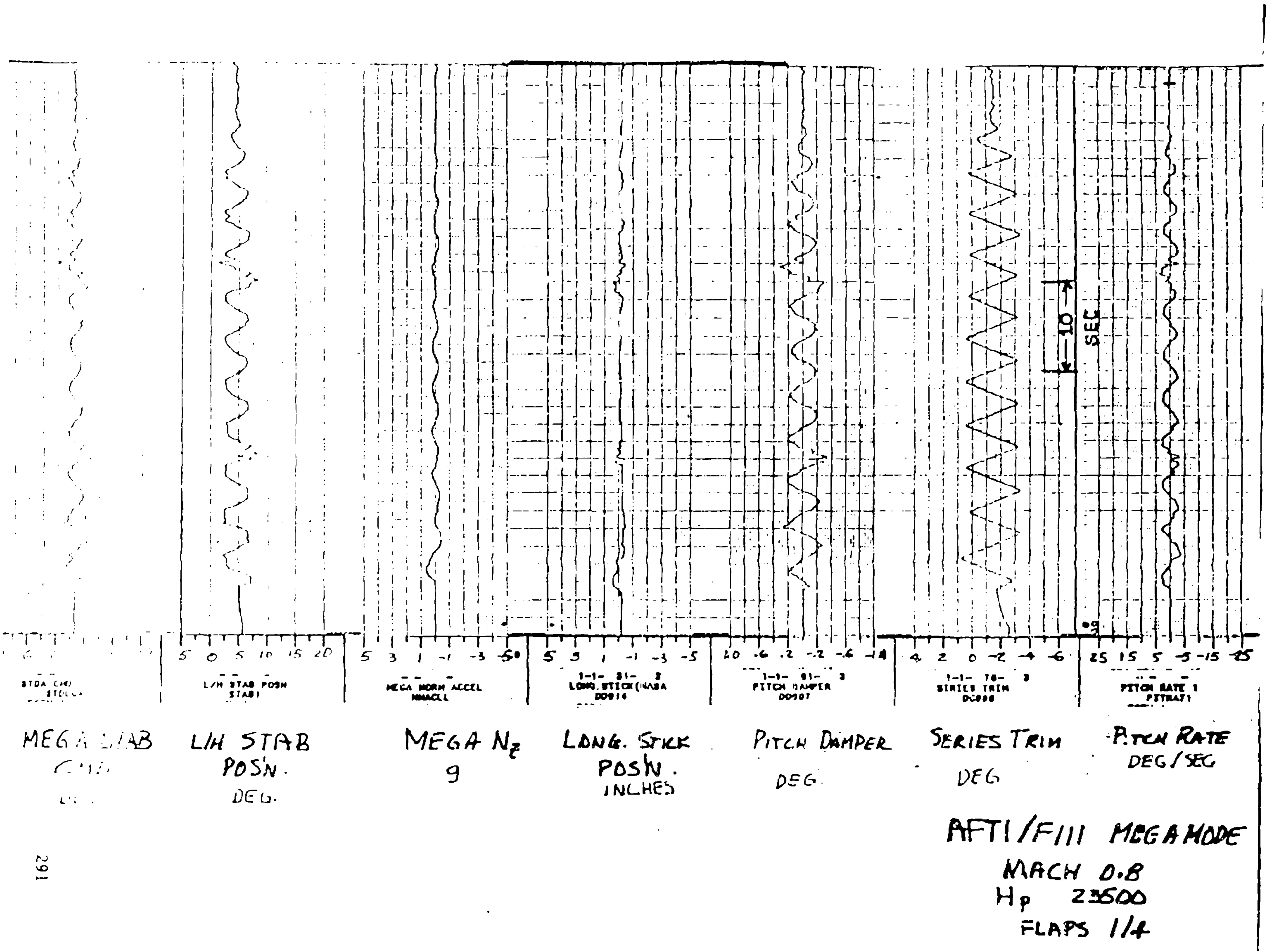
3. <u>X G MEGA STEP + RAP</u>

- ESTABLISH STABILIZED TURN AT X - .5 G, HOLD FOR ~ 5 SEC.
- MAKE MODERATELY SHARP INPUT, CAPTURE X G LOAD FACTOR
- HOLD X G
- SHARP NOSE DOWN PITCH RAP

MACH NO 0.80, ALTITUDE 23500 FT $\delta_F$ MCC

# MEGA / MCC RESULTS

- ASE AND HANDLING QUALITIES SATISFACTORY TO KMEGA = 50%
- AT KMEGA = 70% A PITCH INSTABILITY WAS ENCOUNTERED (FLAPS APPROXIMATELY 1/4)
- FLAP SETTINGS INVESTIGATED



10 SEC
MEGA STAB
L/H STAB POSN.
DEG.
MEGA $N_z$
g
LONG. STICK POSN.
INCHES
PITCH DAMPER
DEG.
SERIES TRIM
DEG
PITCH RATE
DEG/SEC
AFTI/F111 MEGA MODE
MACH 0.8
$H_p$ 23500
FLAPS 1/4

# MEGA/FLAP INVESTIGATIONS

KMEGA = 70%

| FLAP SETTINGS | RESULTS |
|---|---|
| 5/6 | STABLE |
| 5/4 | MARGINAL |
| 5/2 | UNSTABLE |
| 3/6 | UNSTABLE |
| 1/6 | UNSTABLE |
| 3/4 | UNSTABLE |
| 1/4 | UNSTABLE |
| 3/2 | UNSTABLE |

# MEGA/MCC CONCLUSIONS

- AT KMEGA 70% A BOUNDED OSCILLATION EXISTS FOR CERTAIN FLAP SETTINGS
- PROBLEM APPEARS TO BE CAUSED BY GREATER FLAP EFFECTIVENESS AT LOW (< 6°) TE FLAP DEFLECTIONS

# LESSONS LEARNED

- GET AIRCRAFT DERIVATIVES IN FLIGHT BEFORE FINALIZING AUTO MODE DESIGN
- MAKE END-TO-END CHECKS OF ALL SENSOR INPUTS BEFORE FLIGHT
- AVOID SENSORS WHICH RELY ON SMALL CHANGES IN SMALL VALUES FOR COMMANDS
- AVOID ASYMMETRIC SURFACE MOTIONS IN ROLL AXIS IN MLC MODE
- AN "IRON BIRD" SIMULATOR IS NOT A LUXURY
- CONTROL SYSTEM VARIABLE GAIN USEFUL IN EARLY FLIGHT TESTING
- DO NO SET UNREALISTIC HW/SW FAILURE TOLERANCES EG. QBARRE
- ABILITY TO MONITOR CALCULATIONS AND COMMANDS WITHOUT ENGAGING MODE IS VERY HELPFUL

*AFTI/F-111 MAW*
*BRIEFING TO INDUSTRY*

**21 - 22 July 1988**

## SESSION IV -

## AUTOMATIC FLIGHT CONTROL SYSTEM FLIGHT TEST RESULTS

# Handling Quality Analysis of MCC Mode


Joseph L. Conley

NASA Ames Research Center
Dryden Flight Research Facility

AFTI/F-111 MAW
BRIEFING TO INDUSTRY

# HANDLING QUALITIES OBJECTIVES

- Evaluate control system changes that primarily enhance performance
- Evaluate analysis procedures to accomplish first objective

AFTI/F-111 MAW
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## HANDLING QUALITIES MANEUVERS

- Flown in Manual Mode followed by MCC Mode
- Tracking tasks:

  3 g WUT's

  "S" turns

  Simulated terrain following

## PILOT COMMENTS AND RATINGS

| MODE | MANEUVER | RATINGS | COMMENTS |
|---|---|---|---|
| MAN | 3 G TURN HQDT | 3 | PITCH NO PROBLEM |
| MCC | 3 G TURN HQDT | 3 | NOT MUCH CHANGE |
| MAN | 3 G TURN HQDT | 3 | HARD TO STABILIZE ON CANOPY |
| MCC | 3 G TURN HQDT | 2 | PITCH TRACKING EASY |
| MAN | 2 G TURN HQDT | 3 | PITCH NO PROBLEM |
| MCC | 2 G TURN HQDT | 2 | NO CHANGE IN PITCH |

*AFTI/F-111 MAW*
*BRIEFING TO INDUSTRY*

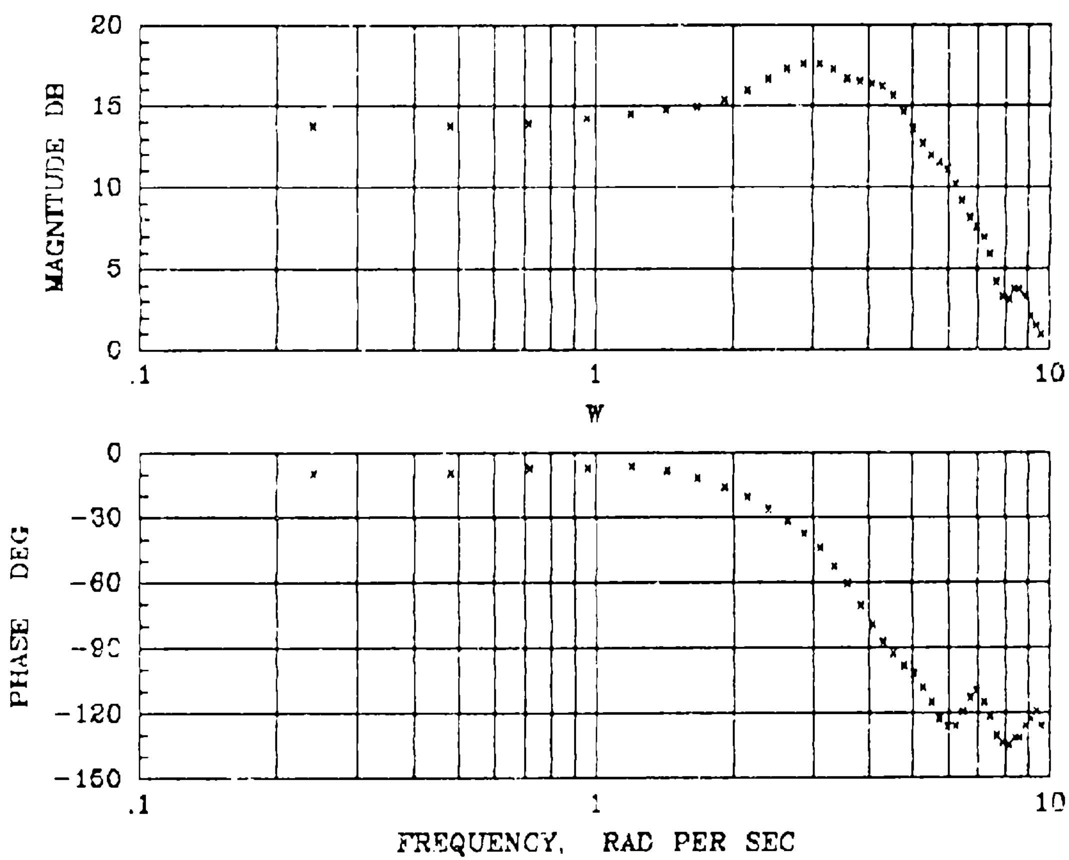
## PILOT COMMENTS AND RATINGS

| MODE | MANEUVER | RATINGS | COMMENTS |
|---|---|---|---|
| MAN | HQDT WUT | 2 | NONE |
| MCC | HQDT WUT | 2 | NONE |
| MAN | S TURN | 3 | NO PROBLEM IN PITCH |
| MCC | S TURN | 3 | INITIAL RESPONSE TO CORRECTIONS A LITTLE FASTER NOW. LITTLE BURBLING. OVERSHOOT IN PITCH, BUT EASILY CONTROLLABLE. |

## HANDLING QUALITIES ANALYSIS

- Tracking maneuver flight data reduced and processed by a fast Fourier transform
- Pitch rate to longitudinal stick transfer functions ($q / \delta_{ep}$) obtained

# PITCH RATE / LONGITUDINAL STICK FREQUENCY RESPONSE



*AFTI/F-111 MAW*
*BRIEFING TO INDUSTRY*

## LOWER ORDER EQUIVALENT SYSTEMS

- $q / \delta_{ep}$ transfer functions approximated by lower order equivalent systems

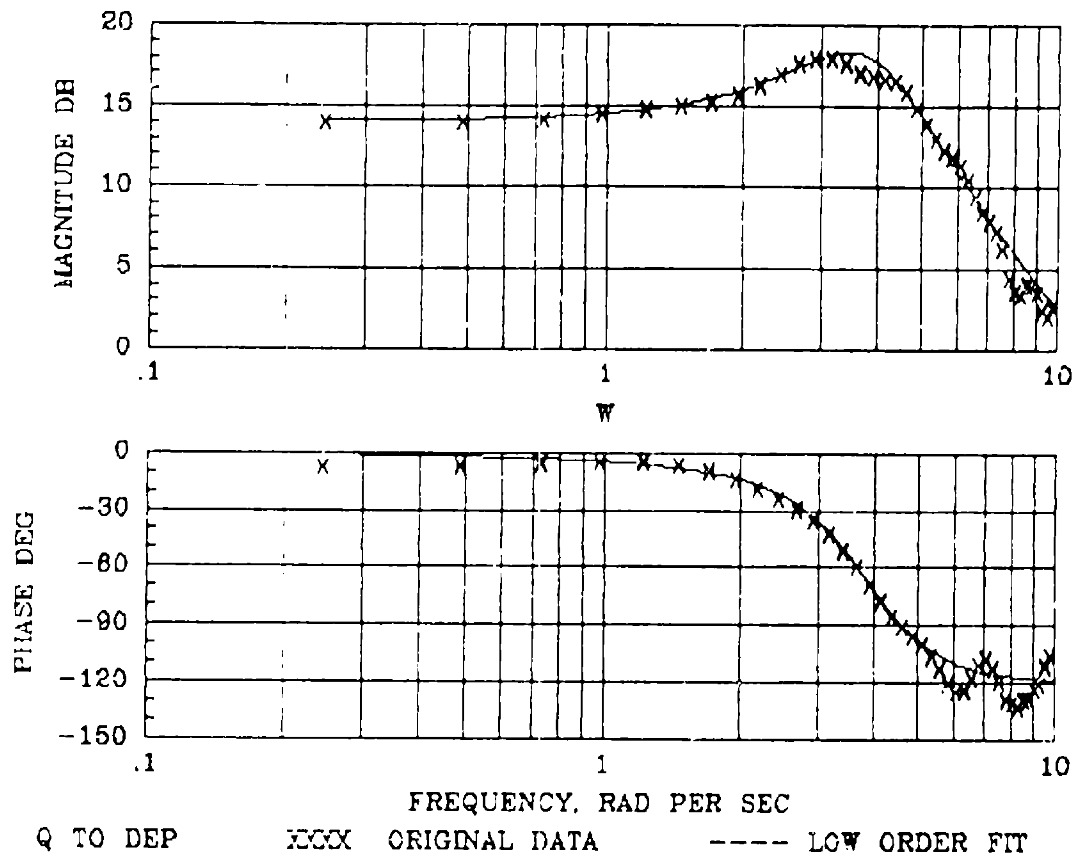
- Results compared to MIL SPEC 8785C criteria:

  equivalent time delay

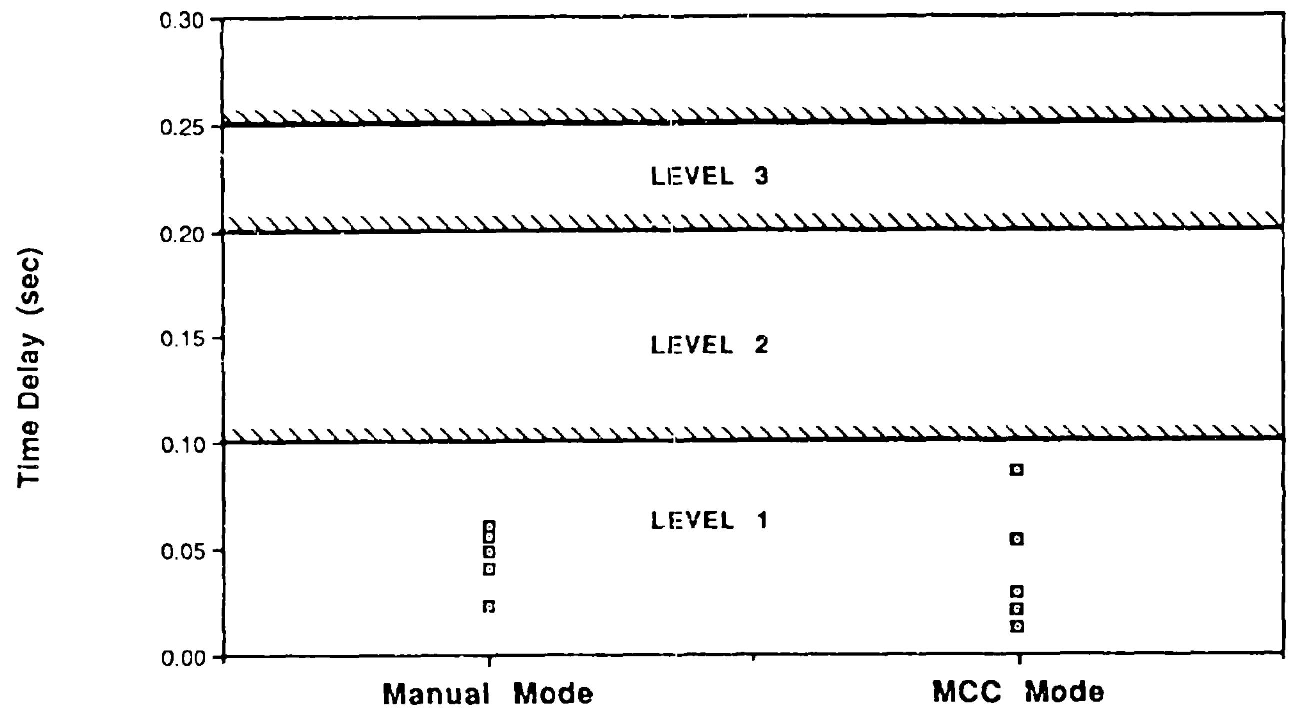
  damping ratio

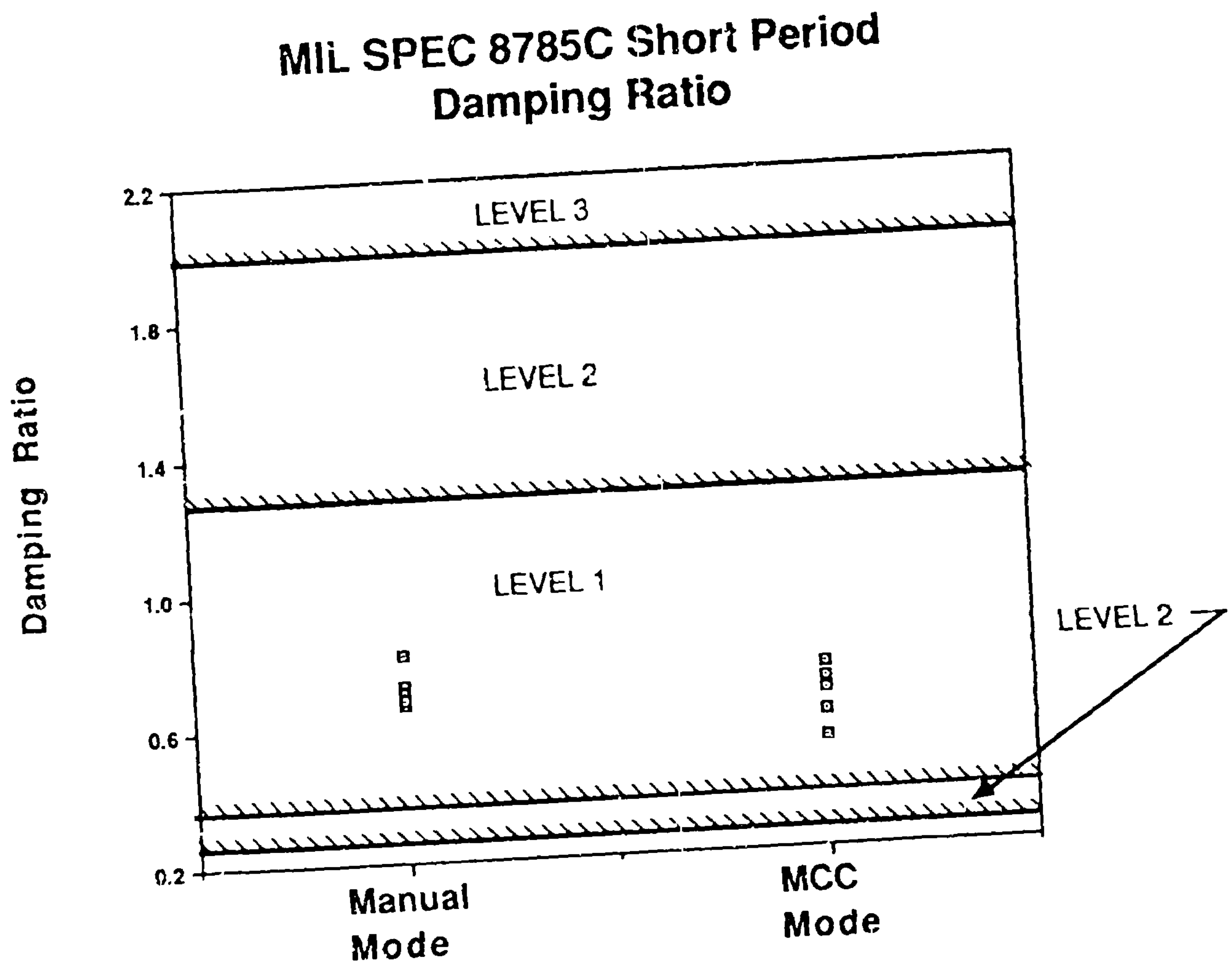
  short period natural frequency vs. load factor per alpha

# Q / δep LOES FREQUENCY RESPONSE

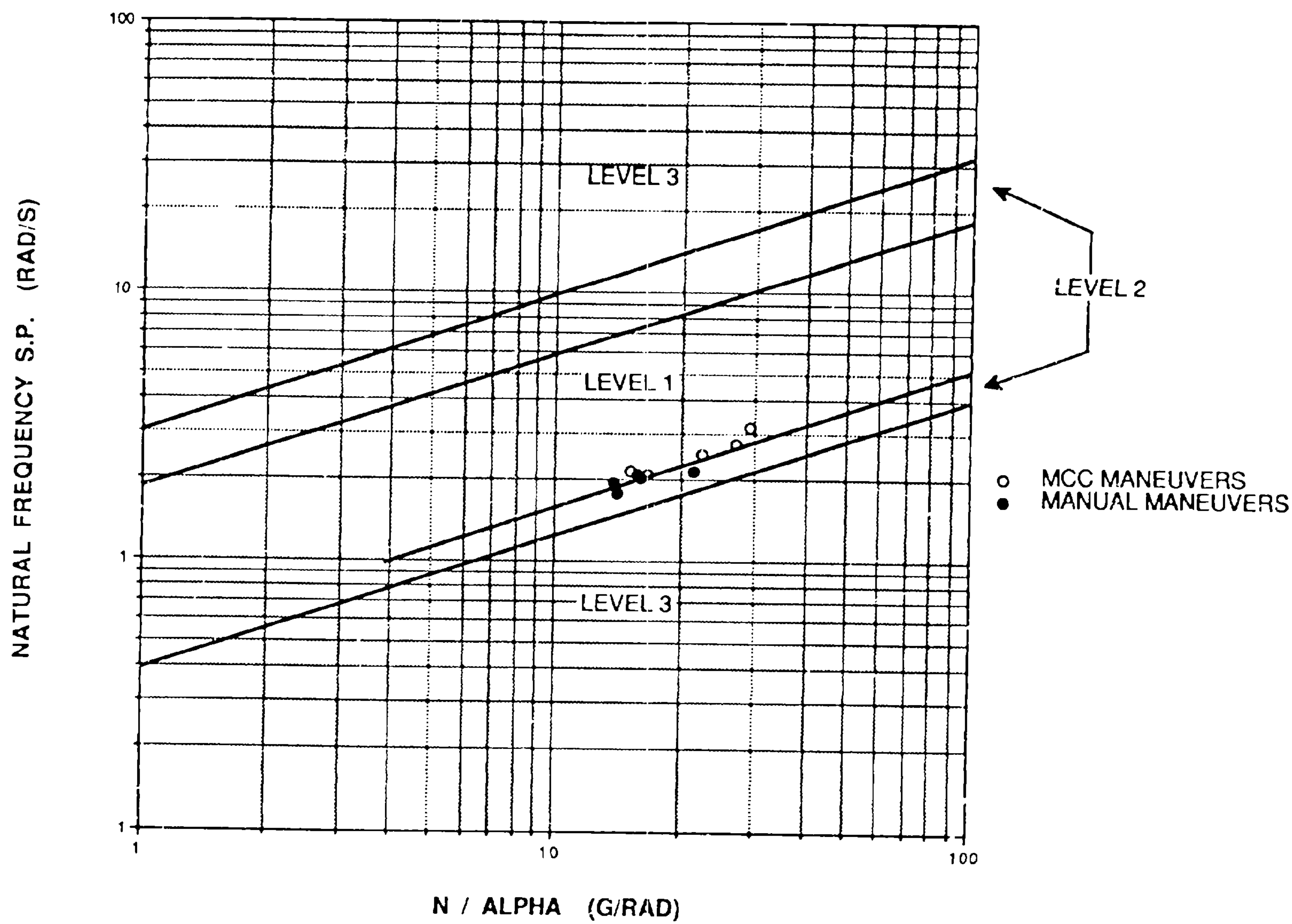


MiL SPEC 8785C Equivalent Time Delay

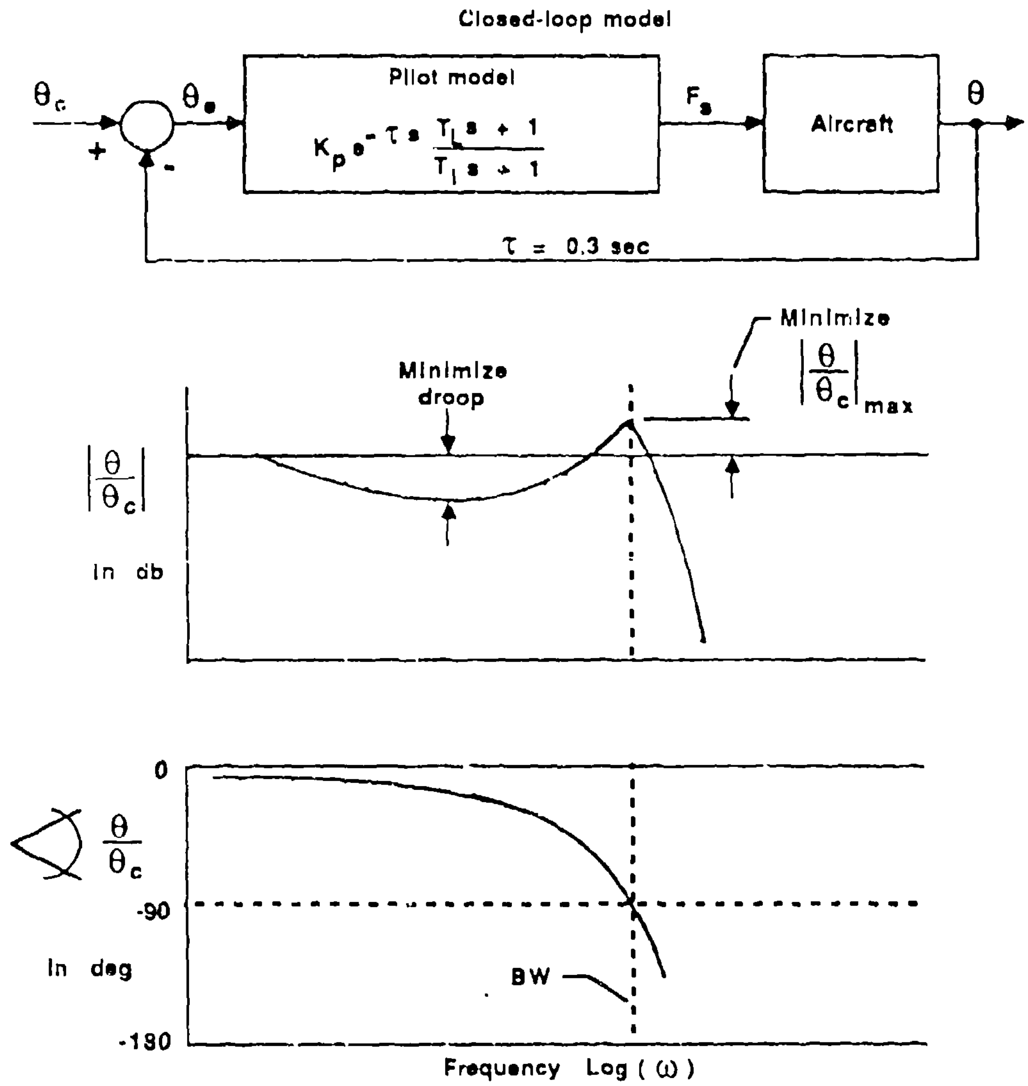



MIL SPEC 8785C Short Period
Damping Ratio
Damping Ratio
2.2
1.8
1.4
1.0
0.6
0.2
LEVEL 3
LEVEL 2
LEVEL 1
LEVEL 2
Manual
Mode
MCC
Mode

## MIL SPEC 8785C Short Period Natural Frequency

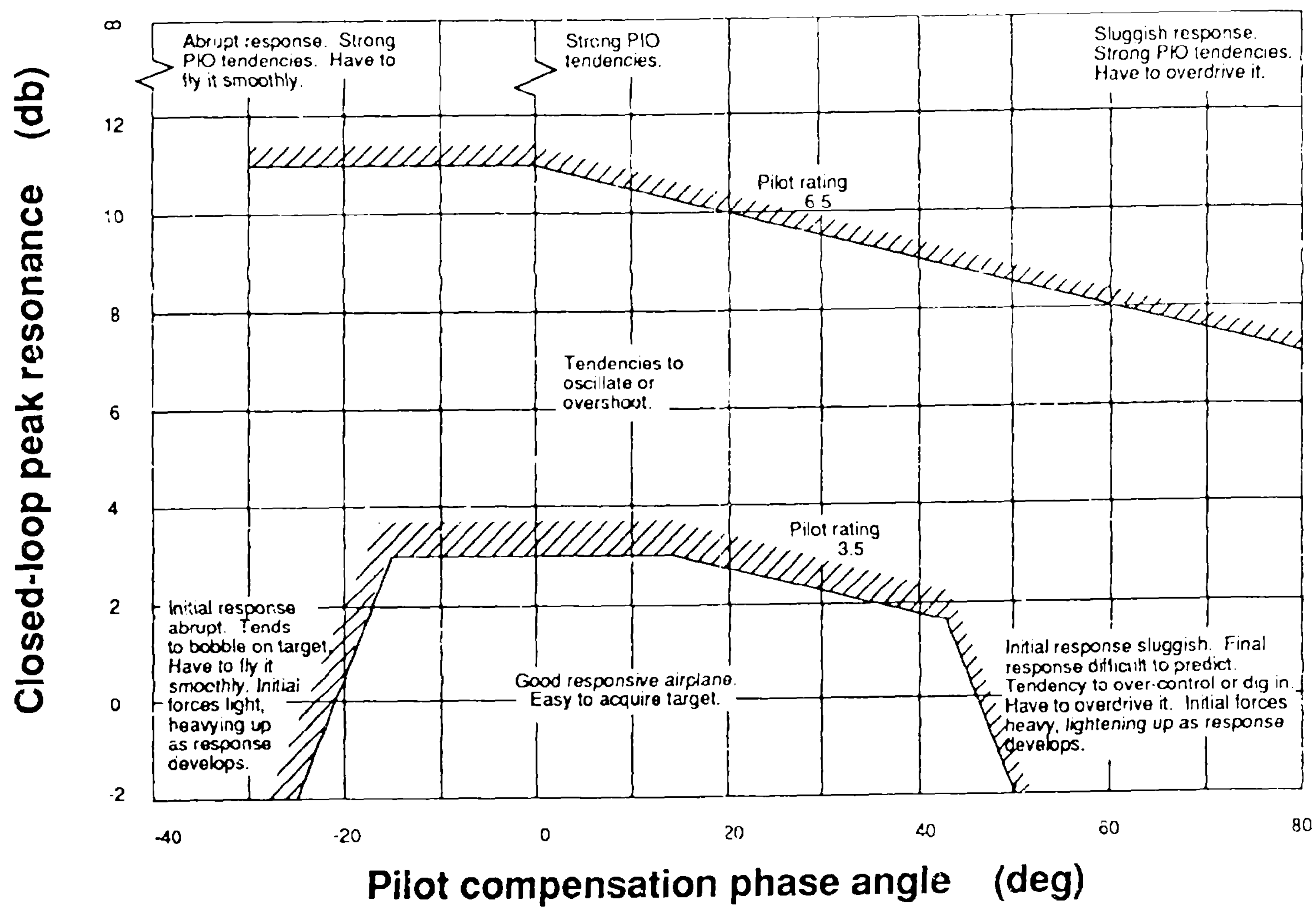


# NEAL-SMITH CRITERION

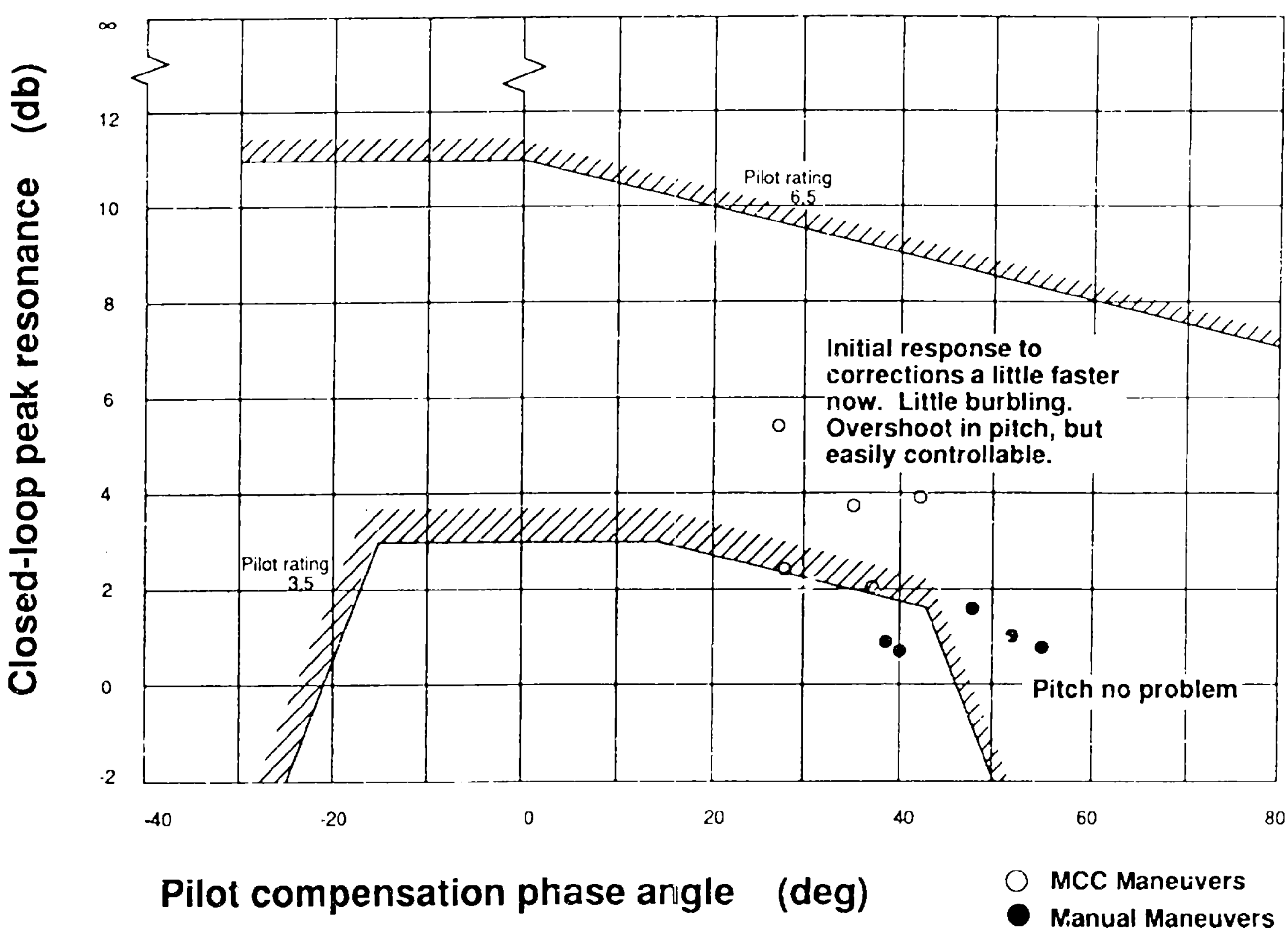



Neal-Smith pilot strategy (closed-loop pilot/vehicle frequency response).

## NEAL-SMITH CRITERION FOR FIGHTER MANEUVERING DYNAMICS



# NEAL-SMITH CRITERION FOR FIGHTER MANEUVERING DYNAMICS



# HANDLING QUALITIES RESULTS

- MIL - F - 8785C longitudinal mode criteria
- Neal / Smith criterion
- Current criteria adequate to predict H. Q. characteristics due to auto modes

# PILOT OBSERVATIONS

- FLIGHT TEST TECHNIQUES
- HANDLING QUALITIES - MANUAL MODE
- HANDLING QUALITIES - CCC, MCC AND MLC
- MEGA MODE OBSERVATIONS
- FINAL THOUGHTS

COL. C.G. FULLERTON

JULY 22, 1988

# FLIGHT TEST TECHNIQUES

- INFLIGHT REFUELING - PLANNED MISSION 3 HOURS
- STICK TRIGGER DISCONNECTS AUTO MODE, RETRACTS FLAPS
- SIMULATOR EXTREMELY VALUABLE TOOL
  - FLIGHT PLAN DEVELOPMENT, INCREASED EFFICIENCY
  - SAFETY ENHANCED-ELIMINATE POINTS THAT EXCEED OR APPROACH LIMITS
  - EASY PARAMETER CHANGE, RESET IMPORTANT
  - USED TO FIND CAUSE OF DESIGN DEFECTS
- MAWSO DUTIES
  - SETUP MAW CONFIGURATION
  - MONITOR POSITION, FUEL, REFUEL PLANNING
  - RELIEF ON LONG FLIGHTS
  - MONITOR LIMITING PARAMETERS
- UPLINK GUIDANCE (RAV)
  - DESIRED/ACTUAL PARAMETER DELTA DISPLAYED ON ADI POINTERS
  - ENHANCES ACCURACY AND EFFICIENCY
- TYPICAL MANEUVERS

| | | |
|---|---|---|
| - WIND-UP TURNS | - CONSTANT NZ TURNS | - PUSHOVER MANEUVERS |
| - SPEED/POWER | - $\alpha$, NZ, $\Theta$ CAPTURES | - STICK RAPS |
| - FORMATION | - AIR-TO-AIR TRACKING | |

2

# HANDLING QUALITIES - MANUAL MODE

- GENERAL RESPONSE, ANY FLAP SETTING - MUCH LIKE STANDARD F-111 (GOOD)
- INFLIGHT REFUELING - NO DIFFERENCE, A/B REQUIRED ABOVE 24000 FT
- INDUCED DRAG WITH LOAD FACTOR DRAMATIC
- FLAP DRAG DRAMATIC (USED AT HIGHER SPEEDS THAN NORMAL F-111)
- INCREASED GROUND ROLL DISTANCE (EMPTY WEIGHT + 9000#, NO GROUND ROLL SPOILERS)
- FAILURE MODES (PRIMARY FCS FAIL)
  - PROCEDURE: USE BACK UP SYSTEM TO LOWER FLAPS, BRAKE MAW, LAND WITH ROLLING STABILON CONTROL
  - DAMPERS ON - REASONABLE ROLL RESPONSE, USE STRAIGHT IN APPROACH TO RUNWAY
  - ROLL DAMPER FAILED - VERY SLUGGISH ROLL RESPONSE, USE LAKEBED
  - ROLL AND YAW DAMPER FAILED - SLUGGISH ROLL, POORLY DAMPED DUTCH ROLL, RUDDER VERY EFFECTIVE - PREFER SINGLE STRING BACKUP SYSTEM FOR LANDING

3

# HANDLING QUALITIES - AUTO MODE

## CCC, MCC AND MLC

- **CRUISE CAMBER CONTROL (CCC)**
  - LOWER FREQUENCY SYSTEM - NO EFFECT ON SHORT PERIOD HANDLING

- **MANEUVER CAMBER CONTROL (MCC)**
  - WING RECAMBERS PER NZ, M TABLE LOOKUP
  - NO APPARENT HANDLING DIFFERENCE FROM MANUALLY SET FLAPS
  - NO APPARENT TRIM CHANGE OR PITCHING EFFECTS AS FLAPS ACTUATE
  - TRACKING OF TARGET AIRCRAFT IMPROVED

- **MANEUVER LOAD CONTROL (MLC)**
  - NO APPARENT PITCH EFFECT WHEN SYSTEM "TRIGGERS"
  - FIRST USES SHOWED ROLL PIO TENDENCY DUE TO DIFFERENCE IN LEFT VS RIGHT WING TRIGGER POINT
  - ELIMINATION OF ROLL AND ROLL RATE FEEDBACK FIXED PROBLEM
  - NOW MODE IS TRANSPARENT TO ROLL AND PITCH HANDLING

- **COMBINATION MODE MCC/MLC**
  - NO INTERACTIVE EFFECTS
  - NO DETECTABLE HANDLING CHANGES

4

# MEGA MODE OBSERVATIONS

- GROUND RESONANCE PROBLEM - LED TO VARIABLE GAIN IMPLEMENTATION
- VERY CONSERVATIVE APPROACH INFLIGHT - SLOWLY INCREASED GAIN STEPS
- FIRST INFLIGHT USE CLEARLY UNSTABLE IN PITCH
    - NZ SIGNAL TO MAW REVERSED POLARITY
    - POLARITY CORRECTED, TESTS RESUMED
- AT FLAPS 5/6, MEGA GAIN UP TO .8, MODE PROVIDES DESIREABLE QUICKENING OF NZ RESPONSE TO STICK COMMAND
- "LURCHINESS" NOTED AT MEGA GAIN > .5 AT LOW CAMBER
    - INITIAL RESPONSE TO PITCH INPUT AS EXPECTED
    - FOLLOWED BY FLAP OSCILLATIONS AND UNDESIRED PITCH MOTIONS
    - PRECISE PITCH CONTROL REQUIRES EXCESSIVE PILOT ATTENTION
    - EFFECT LESS WITH INCREASED WING CAMBER
- SIMULATOR RESPONSE SIMILAR IF PITCHING MOMENT DUE TO TRAILING EDGE FLAP DEFLECTION COEFFICIENT IS DOUBLED
- GUST ALLEVIATION NOT EVALUATED YET

5

# FINAL THOUGHTS

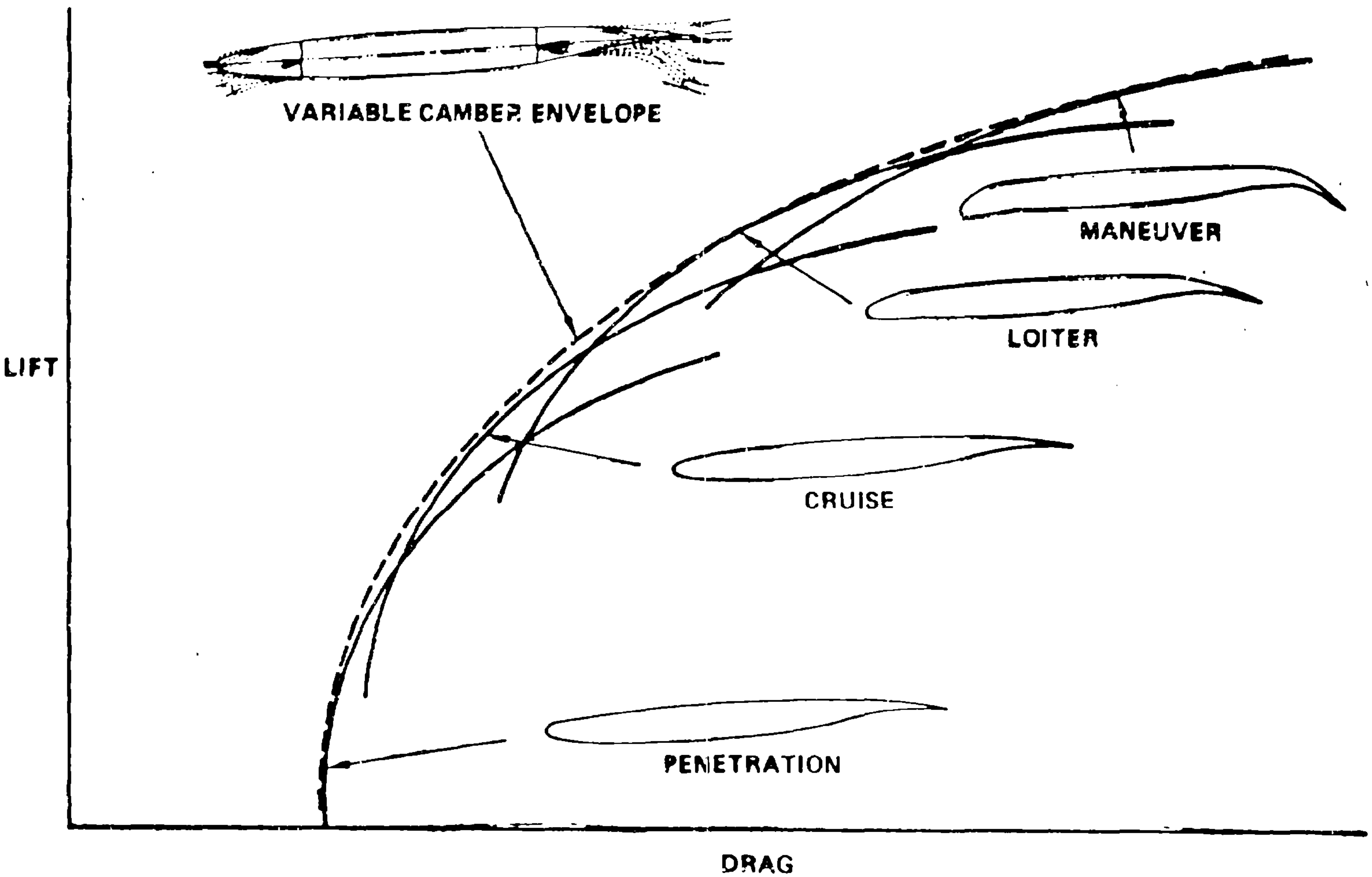
- EXHAUSTIVE GROUND TEST AND SIMULATIONS PAY OFF
- SURPRISES STILL OCCUR IN FLIGHT
- CONSERVATIVE INCREMENTAL APPROACH ADVISED IF ANY DOUBT EXISTS

6

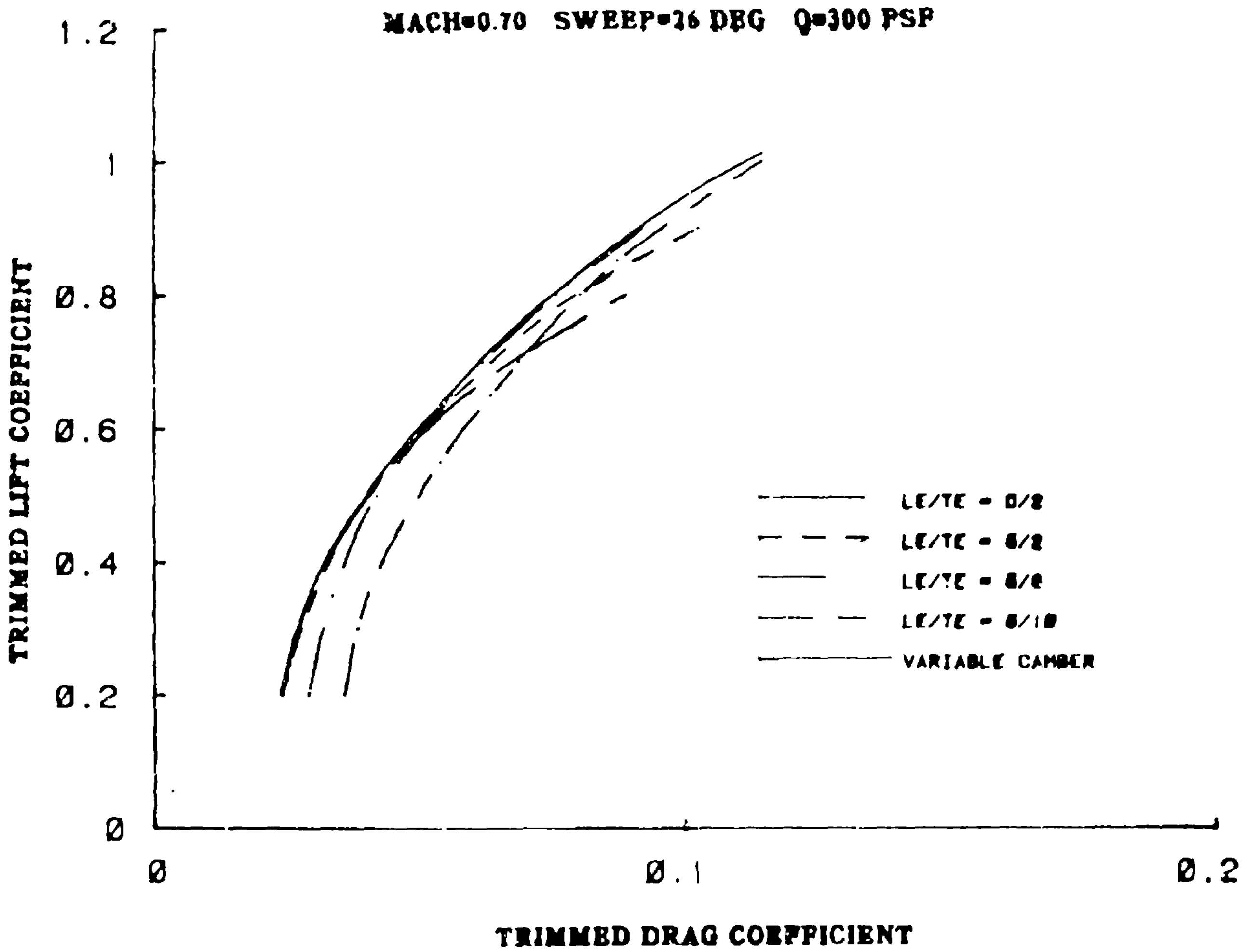
# AFTI/F-111
# MISSION PERFORMANCE

GLENN W. HARSHBERGER
CHIEF AERODYNAMICIST
AFTI/F-111 ADPO

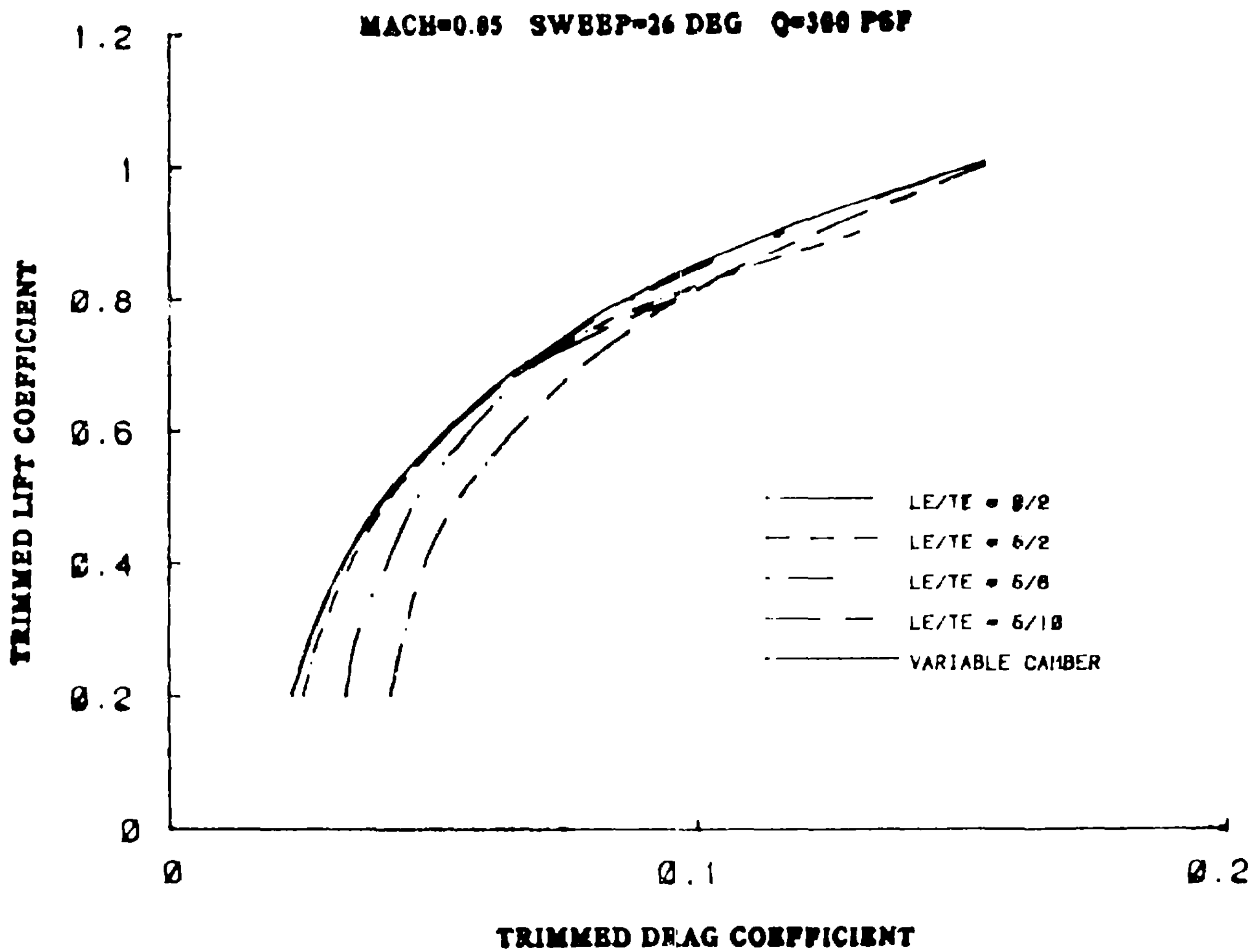
# Mission Adaptive Wing
# Aerodynamic Characteristics



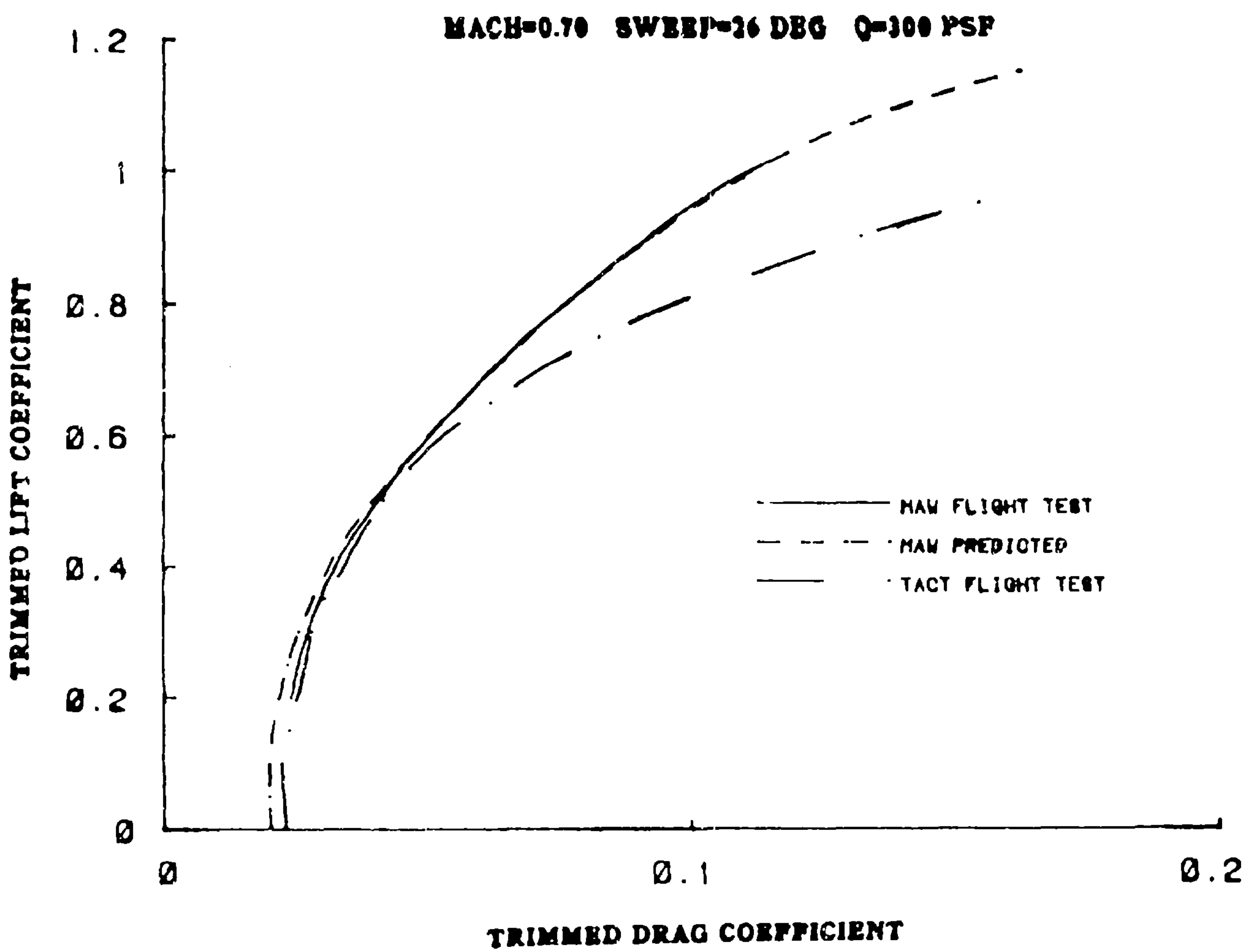
# VARIABLE CAMBER ENVELOPE



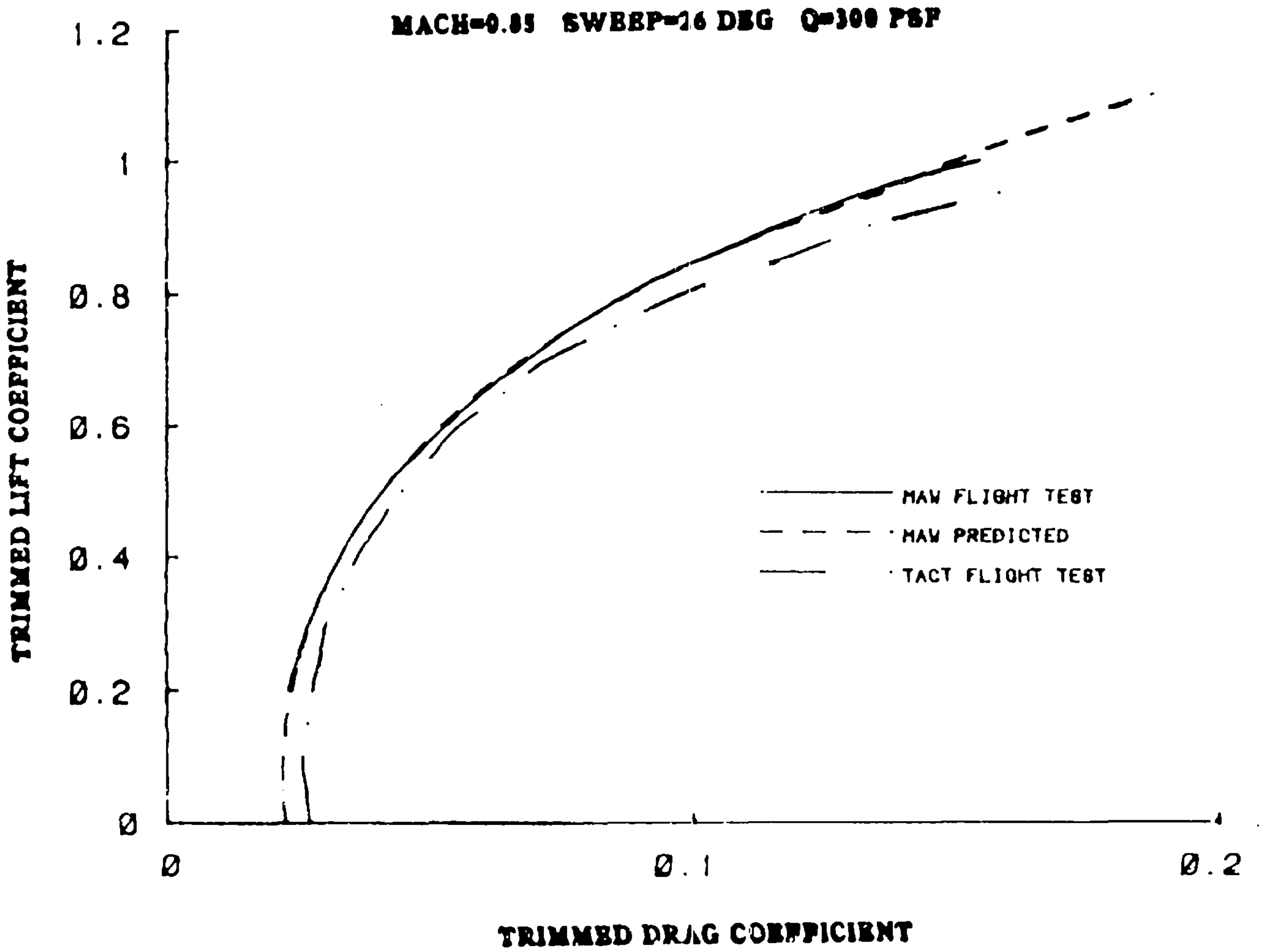
# VARIABLE CAMBER ENVELOPE



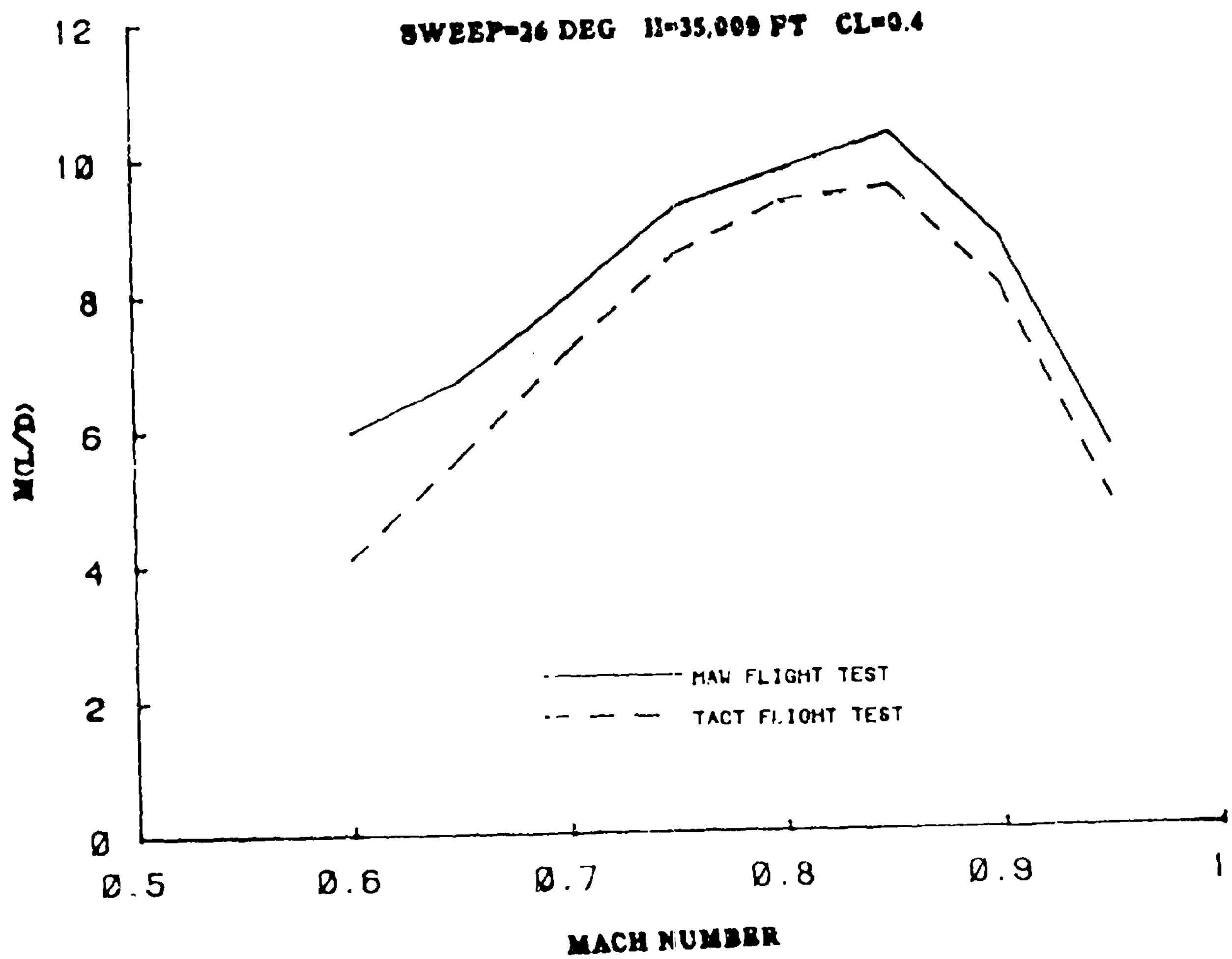
# DRAG POLAR COMPARISON



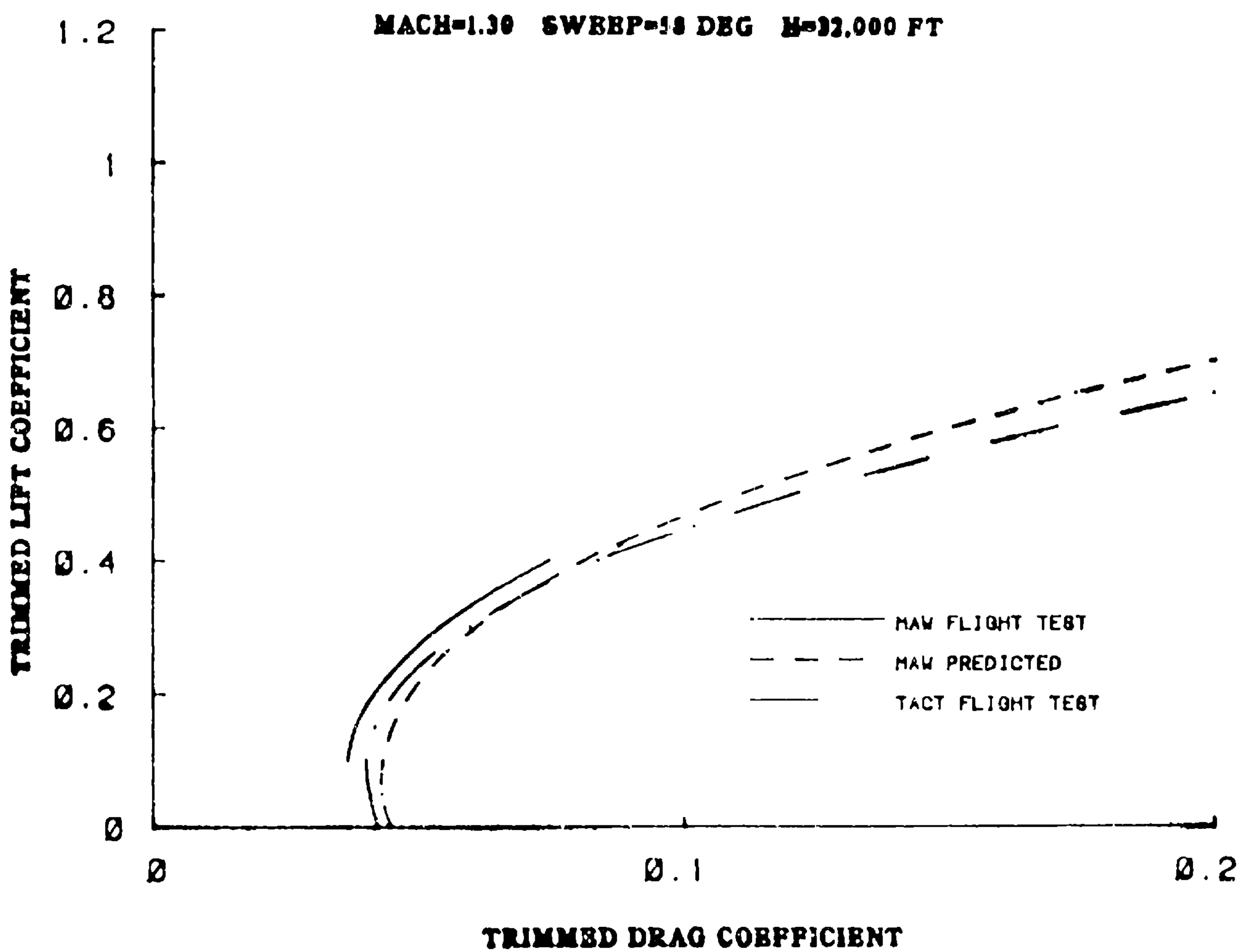
# DRAG POLAR COMPARISON



# CRUISE EFFICIENCY



# DRAG POLAR COMPARISON



# NSEG OVERVIEW

NSEG

- ENERGY MANEUVERABILITY
- MISSION ANALYSIS

**ENERGY MANEUVERABILITY**

- EXAMINE MANEUVERABILITY OF AIRCRAFT
- DEVELOP VARIED FLIGHT ENVELOPES
- COMPARE FLIGHT ENVELOPES OF TWO DIFFERENT AIRCRAFT

**MISSION ANALYSIS**

- INVESTIGATE RANGE/PAYLOAD PERFORMANCE OF AIRCRAFT
- COMPARE AIRCRAFT CONFIGURATIONS AND FLIGHT PROFILRS
- DEVELOP REALISTIC FLIGHT PROFILES FOR OTHER APPLICATIONS

# BASIC INPUT DATA

- AERODYNAMIC DATA
  - CLEAN AIRCRAFT DRAG POLARS
  - EXTERNAL STORE DRAG
  - MACH, DYNAMIC PRESSURE, LIFT COEFFICIENT LIMITS
  - REYNOLDS NUMBER CORRECTIONS

- PROPULSION DATA
  - MAX DRY (MILITARY) THRUST AND FUEL FLOW (OR SFC)
    - FF=f(H,M,POWER SETTING)
  - PARTIAL AFTERBURNER (WET)
    - NOT REQUIRED
  - FULL AFTERBURNER THRUST AND FUEL FLOW (OR SFC)
    - FF=f(H,M)

- WEIGHTS AND CONFIGURATION DATA
  - AIRCRAFT EMPTY AND TAKE-OFF GROSS WEIGHT
  - FUEL AND EXPENDABLE STORES WEIGHT
  - EXPENDABLE STORES CONFIGURATION
  - AERO REFERENCE AREA

## AERODYNAMIC MODELS

- TACT
  - "TACT FLIGHT DERIVED LIFT AND DRAG CHARACTERISTICS," AFFTC-TR-77-12. JULY 1977. (VOLUME I)
  - CD = F(CL,M,Q.SWEEP)
  - MACH = .5 TO 2.0
  - Q = 200 TO 1100 PSF
  - SWEEP = 26 & 58
- AFTI/F-111
  - CD = F(CL,M,Q.SWEEP.LE.TE)
  - MACH = .65 TO 1.3
  - SWEEP = 26 & 58
  - $58^{0}$ SWEEP FLOWN AT H=30,000 FT.
  - $26^{0}$ SWEEP PRIMARILY FLOWN AT Q = 300 PSF

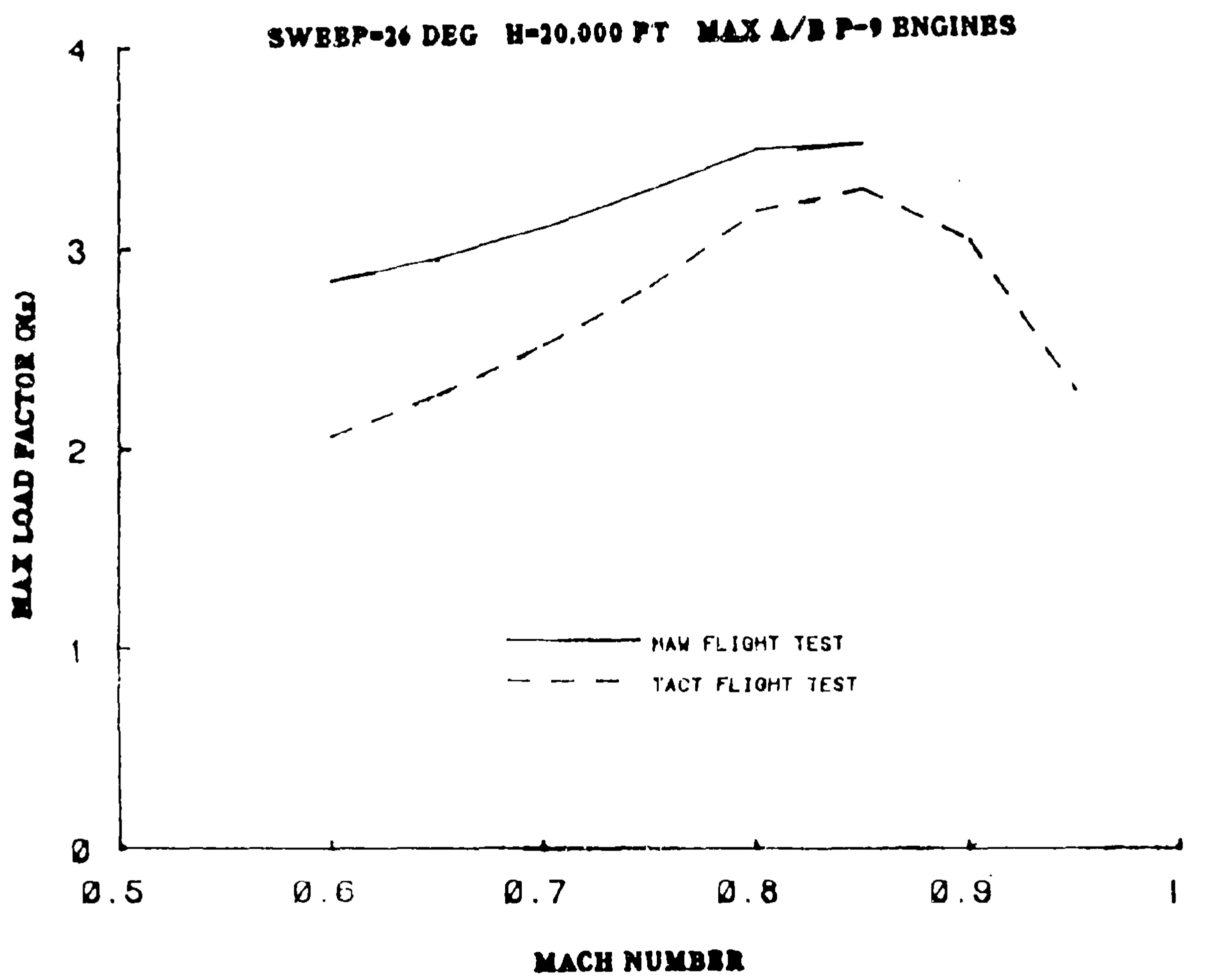
## THRUST MODEL

- TF30-P-9 ENGINES
  - "PROPULSION DATA SUBSTANTIATION STANDARD AIRCRAFT CHARACTERISTICS CHARTS AND REGULAR FLIGHT MANUAL F-111D AIRCRAFT," GENERAL DYNAMICS REPORT FZA-12-8002, OCT 1970.
  - MACH = 0 TO 2.5
  - ALTITUDE = 0 TO 65,000 FT.
  - FN, $W_F$ = F(M,H)

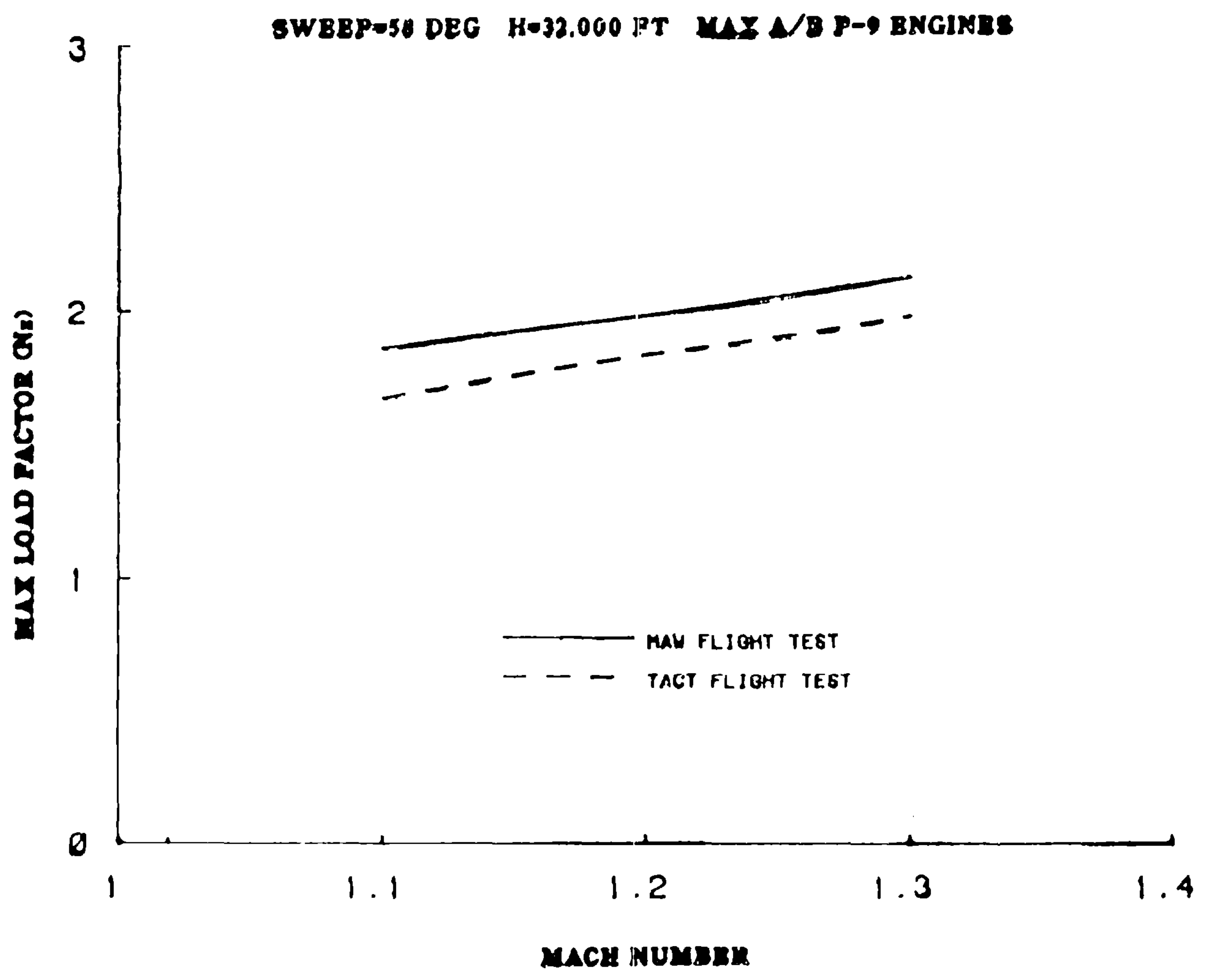
PRODUCTION AIRCRAFT WEIGHT SUMMARY (LBS.)

| | TACT | MAW | $\Delta$ |
|---|---|---|---|
| OPERATING WEIGHT | 49287 | 49965 | 678 |
| FUEL | 26746 | 26746 | 0 |
| TAKEOFF WEIGHT | 76033 | 76711 | 678 |

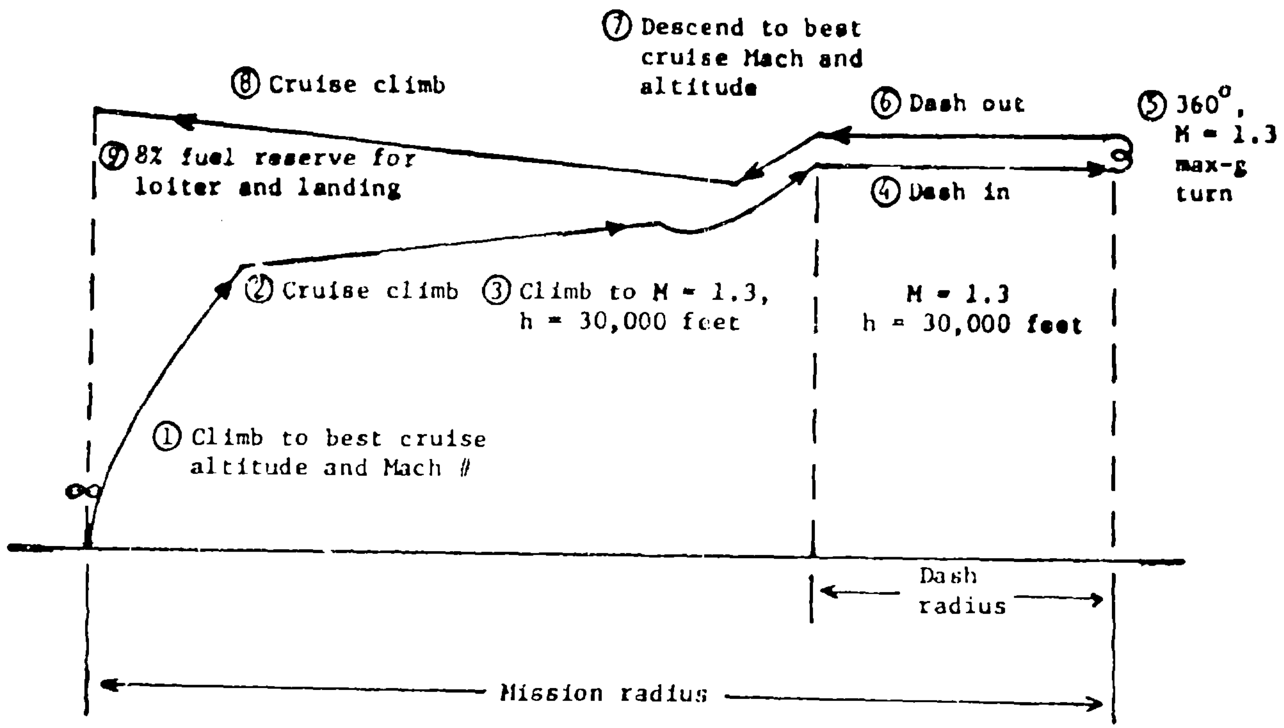
# SUBSONIC MANEUVERABILITY COMPARISON



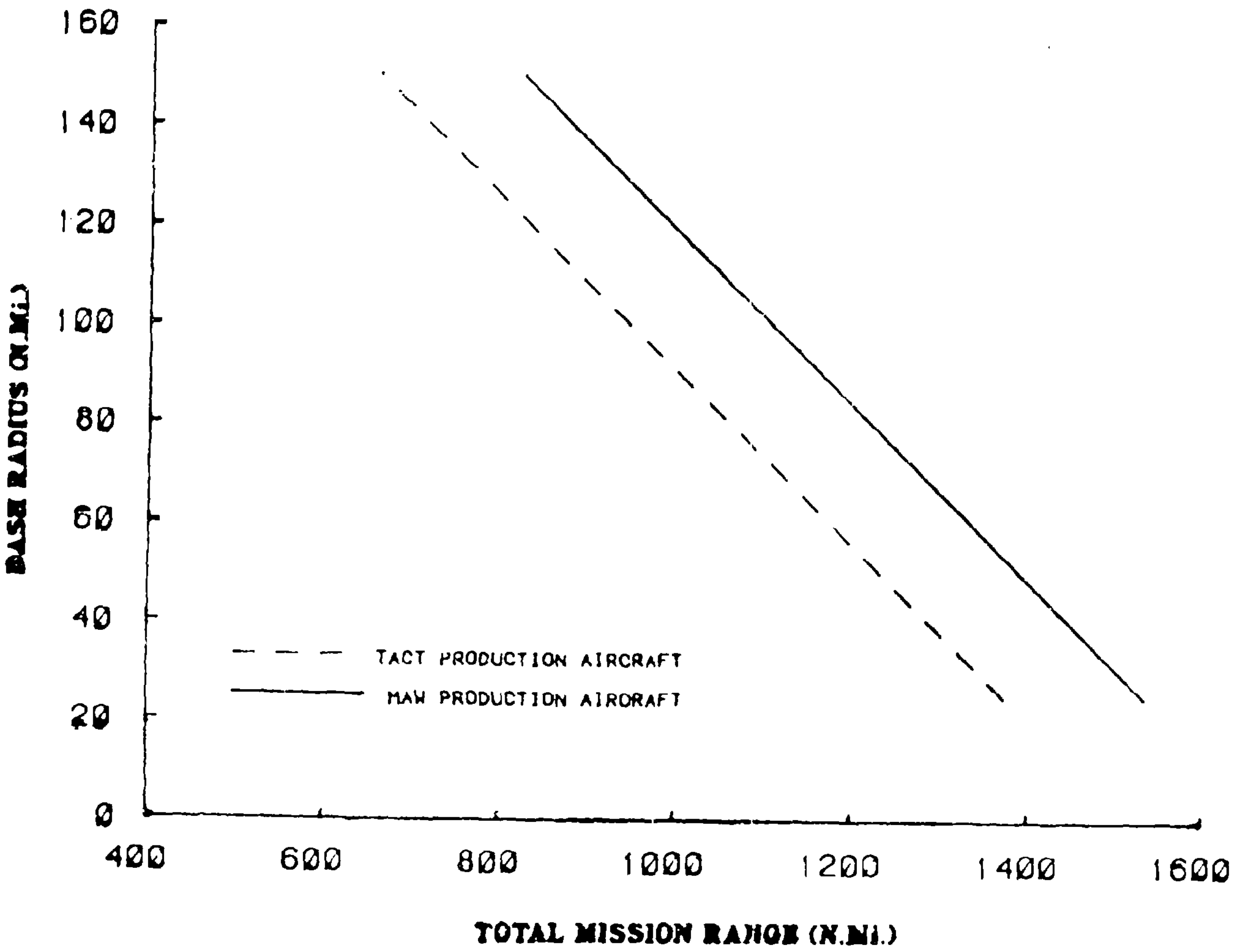
# SUPERSONIC MANEUVERABILITY COMPARISON



# MISSION PROFILE



# MISSION RANGE COMPARISON



SESSION V

MAW TECHNOLOGY TRANSITION

# CRUISE CAMBER CONTROL
## for the AFTI/F-111 Missions Adaptive Wing

Larry D. Brock
Col USAFR

Briefing to Industry
Dayton, Ohio
21-22 July 1988

Flight Dynamics Laboratory
Air Force Wright Aeronautical Laboratories
Aeronautical Systems Division
Air Force Systems Command
Wright Patterson Air Force Base, Ohio 45433

AFTI/F-111
MAW

# CRUISE CAMBER CONTROL (CCC)

## Purpose

Adjust the camber of the Mission Adaptive Wing during cruise operation to provide the optimum shape for the current conditions. The optimum shape is the one that maximizes speed by minimizing the total effective drag.

## Requirements

The CCC mode must operate automatically and autonomously in a self-optimizing process without the need for extensive *a prioi* aircraft performance data.

# ADVANTAGES OF CCC

- Optimizes Cruise Performance
  - Increases speed or
  - Increases range
- Self Adaptive
  - To variations in a particular aircraft over time.
  - To variations from aircraft-to-aircraft in the fleet.
- Self Contained
  - Not dependent on acquiring extensive and expensive wind tunnel and flight test data.

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MAW

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# CCC STUDIES

- A simulation program was developed to study automatic camber control issues.
- Cruise camber optimization strategies were studied.
  - Techniques using test camber perturbations were determined to be the most promising.
- The effects of turbulence were studied.
  - Sensor data filtering was needed.
  - CCC mode was predicted to be functional with turbulence levels that are experience 98% of the time at the expected cruise altitudes.
- The potential for climb optimization was investigated.
  - Performance of automatic camber optimization during climb is expected to be marginal due to the difficulty of accurately predicting performance in a changing dynamic environment.

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# BASIC OPTIMIZATION STRATEGY

- Inject a step pertubation in the camber angle.
- Measure the dynamic response of the aircraft using available sensor data.
- Assess the effects of the camber change using the dynamic response of the aircraft.
- Make additional changes based of the assessment of the previous camber change.

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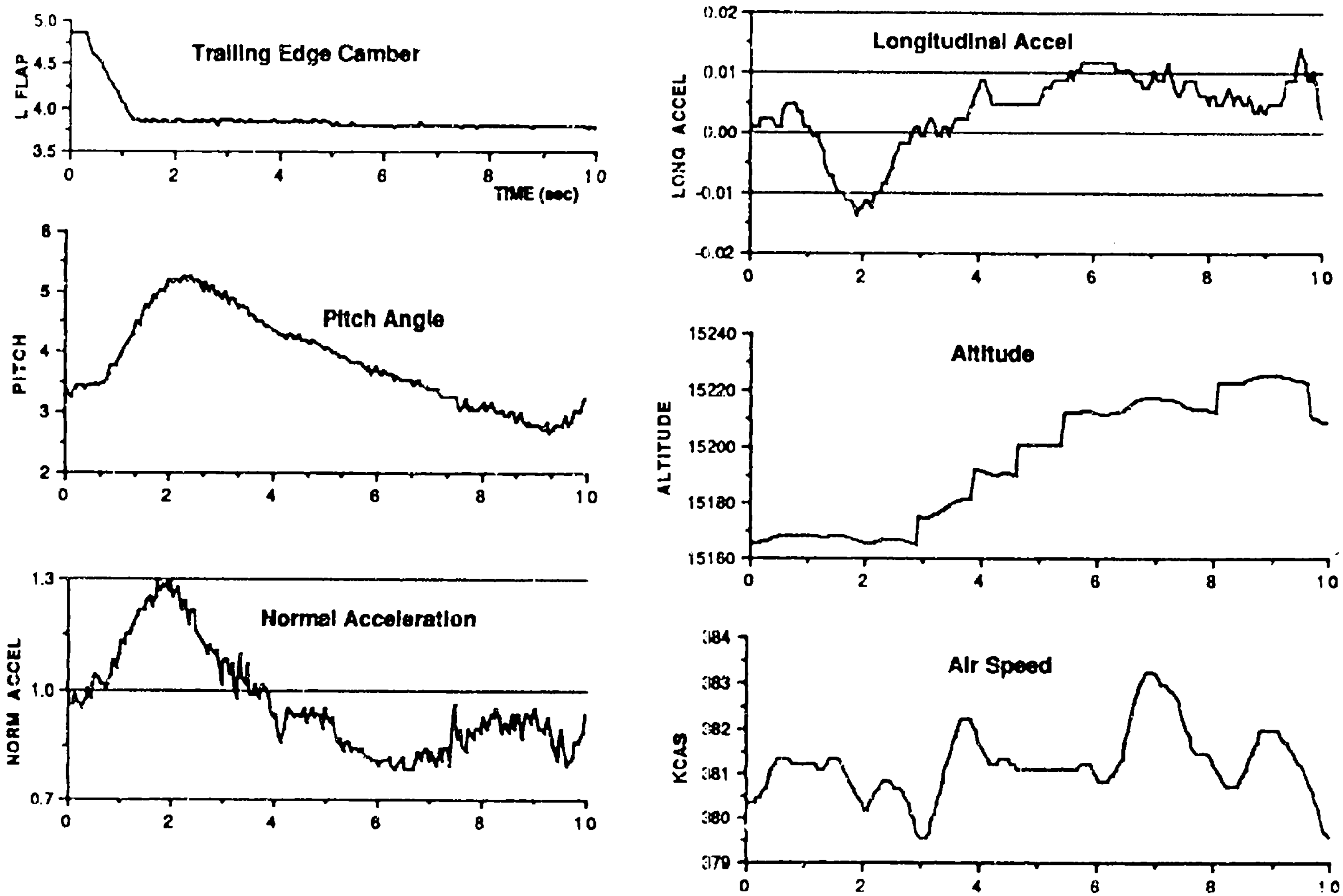
# CCC DESIGN CHALLENGES

- No available sensor measurement gives an immediate and direct indication of the desired effect of a camber change.
  - Velocity is slow to respond to camber change.
  - Acceleration measurements are difficult to interpret because of corruption from other effects.
- Primary difficulty is the complex dynamic response of the aircraft to a camber change.
  - Immediate response of the aircraft to a camber change is a disruption of the pitch balance.
  - There are then changes in the vertical plane which must be corrected by the altitude hold autopilot.
  - Finally there is the change in horizontal speed which is the effect desired.

# DYNAMIC RESPONSE TO CAMBER CHANGE

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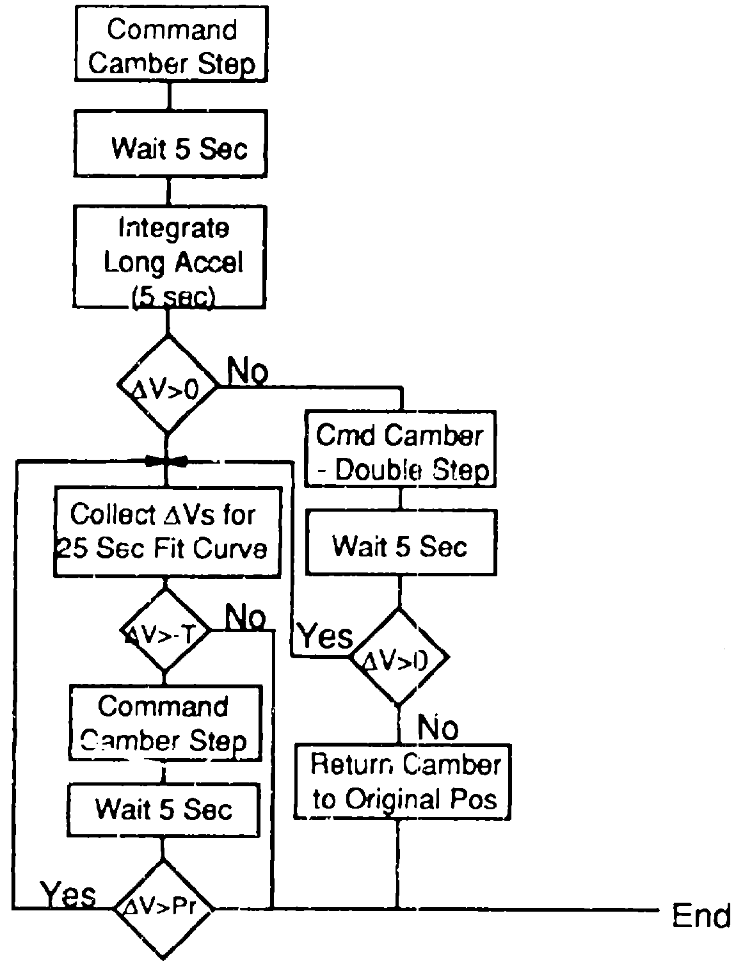
# CURRENT IMPLEMENATION OF CCC

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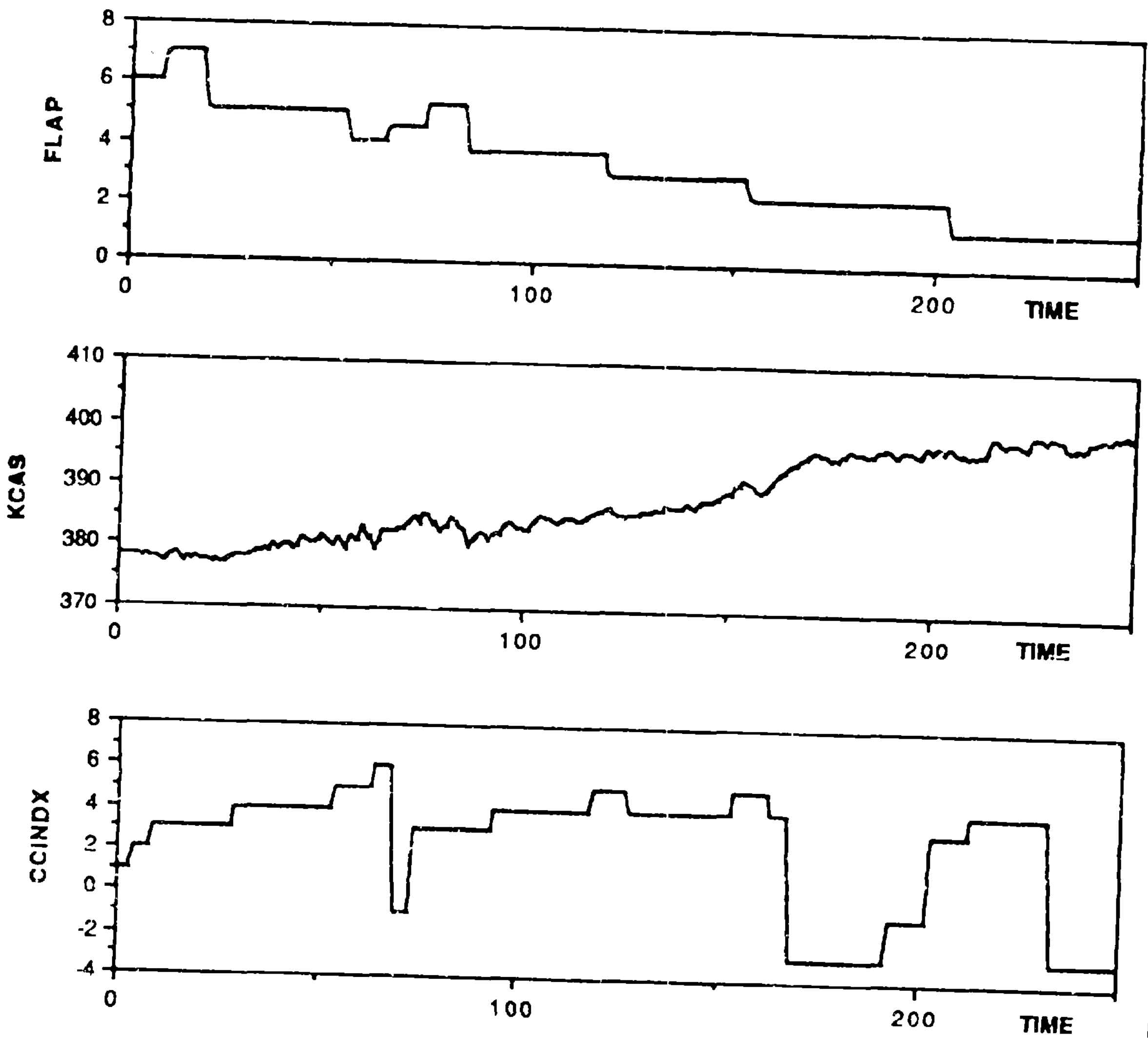
# FLIGHT TEST OF CCC

- There have been nine tests of the CCC mode during three flights with multiple search sequences during several of these tests.

- The performance of the CCC mode has not been as good as expected.
  - — The search technique was able to identify the correct direction to begin the search sequences.
  - — In most of the search sequences, the search either stopped prematurely or continued to change the camber beyond the region of the known optimum value.

# RESULTS OF SELECTED FLIGHT TESTS

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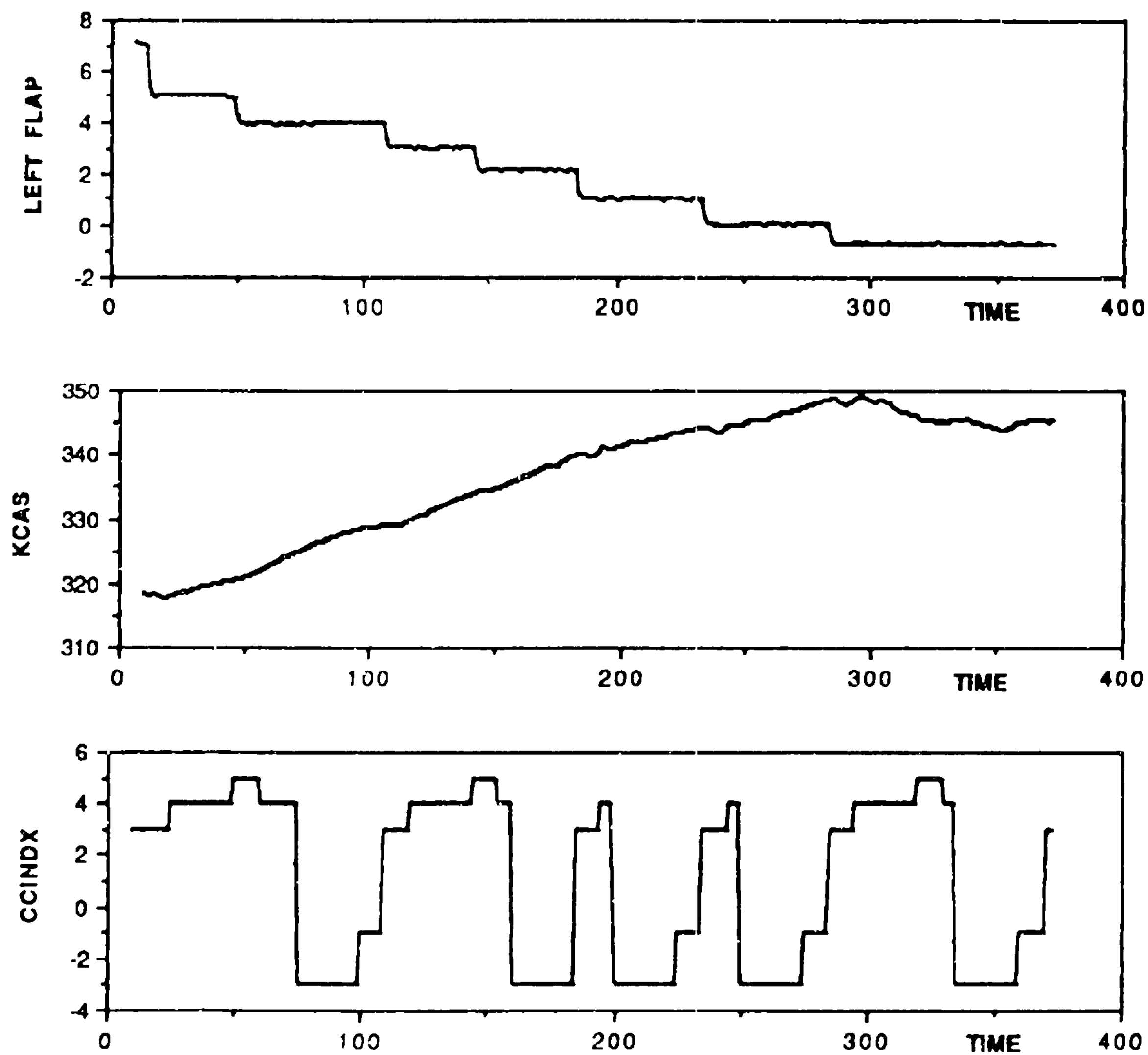
# RESULTS OF SELECTED FLIGHT TESTS (cont)

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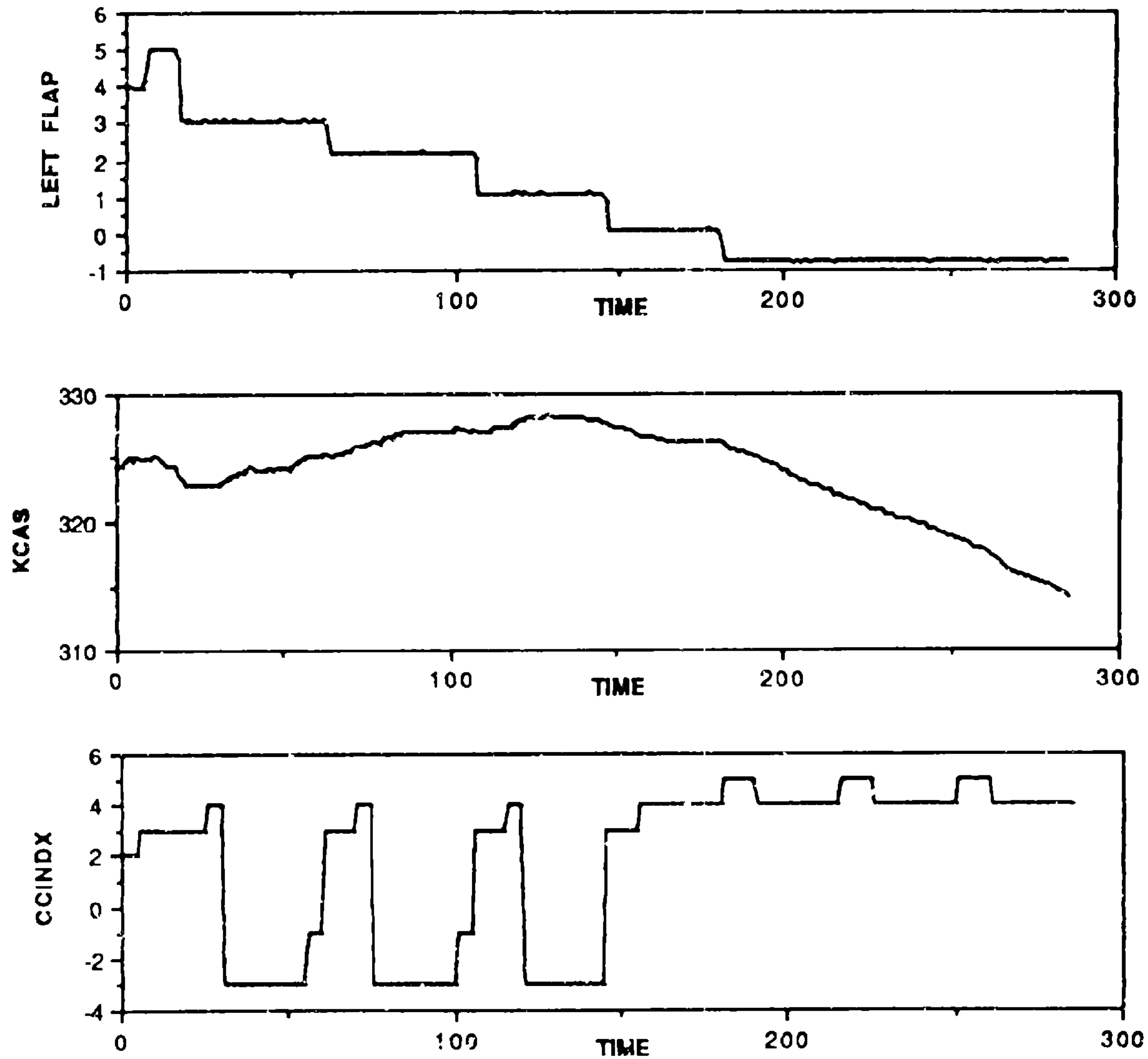
# RESULTS OF SELECTED FLIGHT TESTS (cont)

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# PRELIMINARY ANALYSIS OF THE FLIGHT TEST RESULTS

- The primary difficulty in the performance of the CCC mode appears to be corruption and noise in the acceleration measurements.
  - The accelerometers used are body mounted. A technique of zeroing acceleration at the beginning of each five second period was used to remove undesired bias effects such as those due to pitch angle.
  - The effects of pitch due to the transients introduced by the camber change and other noise appears to be a major cause of the poor performance.

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# FUTURE PLANS FOR THE CCC MODE

- A modification of the CCC mode is being planned to improve performance.
  - This modification will used velocity instead of acceleration.
  - An estimate of the effect of a camber change is made by measuring the change in velocity.
- Velocity has the advantage of:
  - being a more direct measure of the desired aircraft performance characteristic, and
  - not being as influenced by undesired aircraft dynamic characteristics.

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# CONCLUSIONS

- The availability of a CCC mode will be a valuable asset for an aircraft that has a variable camber wing.

- Even though the flight test of the current implementation of the CCC mode has not been successful, the flight test data shows that information is available to implement a successful CCC mode.

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*BRIEFING TO INDUSTRY*

21 - 22 July 1988

## SESSION V - MAW TECHNOLOGY TRANSFER

### Post Flight Analysis of Automatic Flight Control Modes


Joseph L. Conley

NASA Ames Research Center
Dryden Flight Research Facility

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## MODELS OF THE AUTO MODES

- Independent verification of mode implementation
- Provided the capability for access to internal variables
- Facilitated analysis for proposed mode modifications

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## MODELING APPROACH

- All modes computer modeled for non-real time analysis
- Included capability of accepting flight measured sensor and command inputs
- Results included comparison of simulated auto mode commands with flight results

## AUTO MODE ANALYSIS

- CCC Mode - functional evaluation and recommendation for modification
- MCC Mode
- ME/GA Mode

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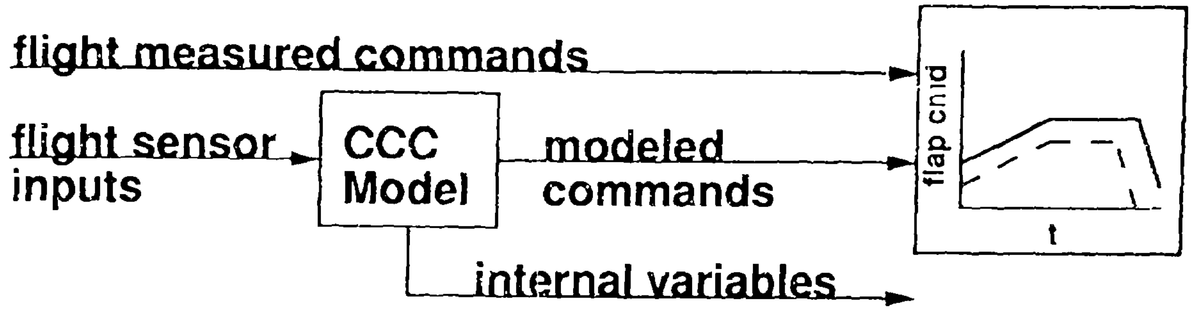
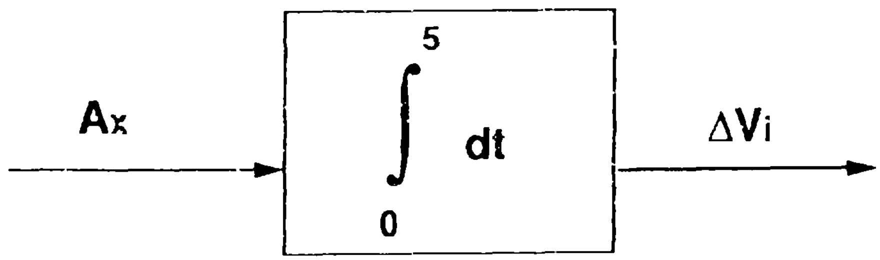
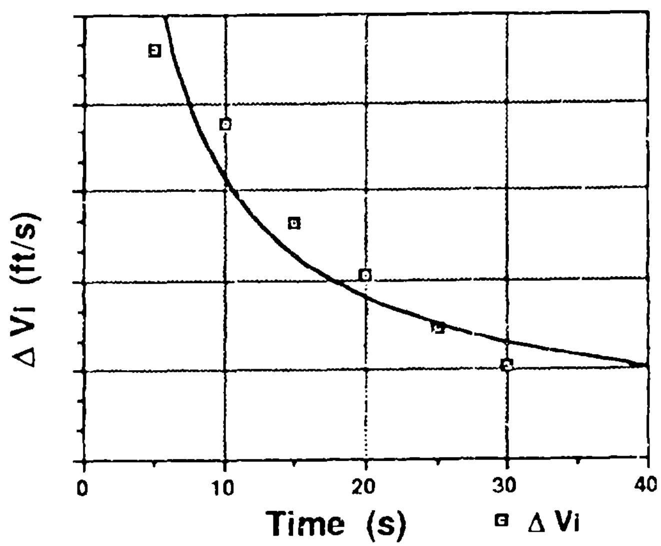
# CCC MODE ANALYSIS



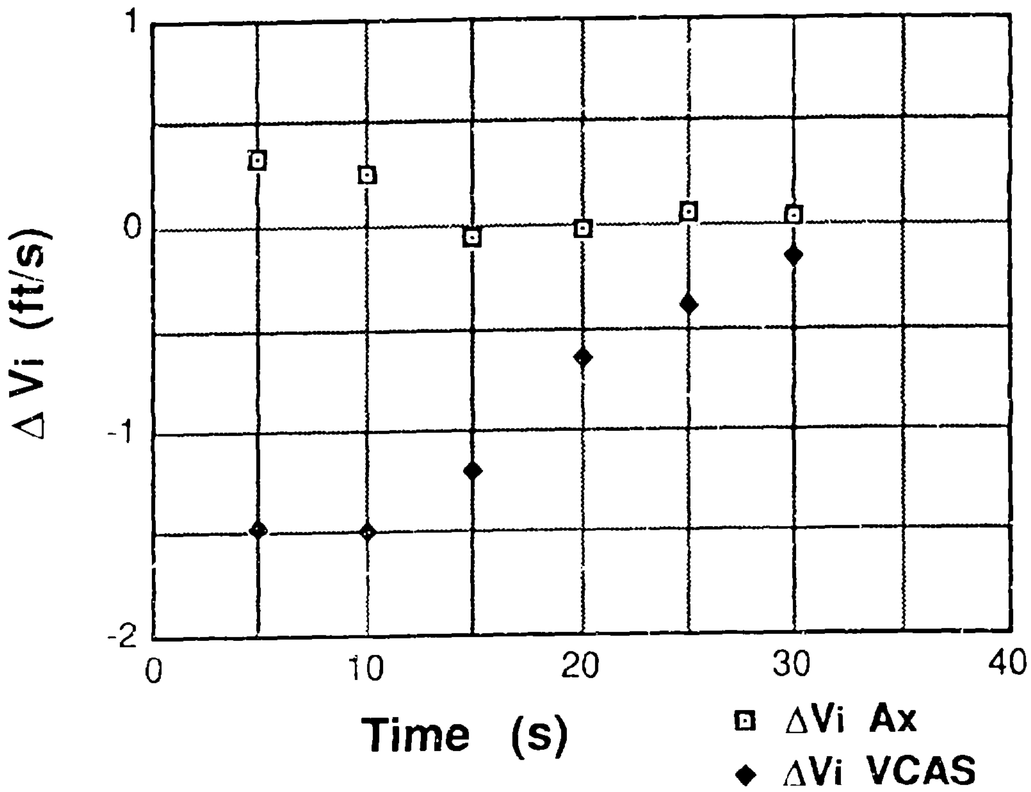

- Verified mode was functioning as designed
- Determined poor mode performance was caused by sensor input and not the mode logic
- Facilitated modification of mode using airspeed as sensor input

# CCC ESTIMATION PROCESS (IDEAL)



# CCC ESTIMATION PROCESS (ACTUAL)



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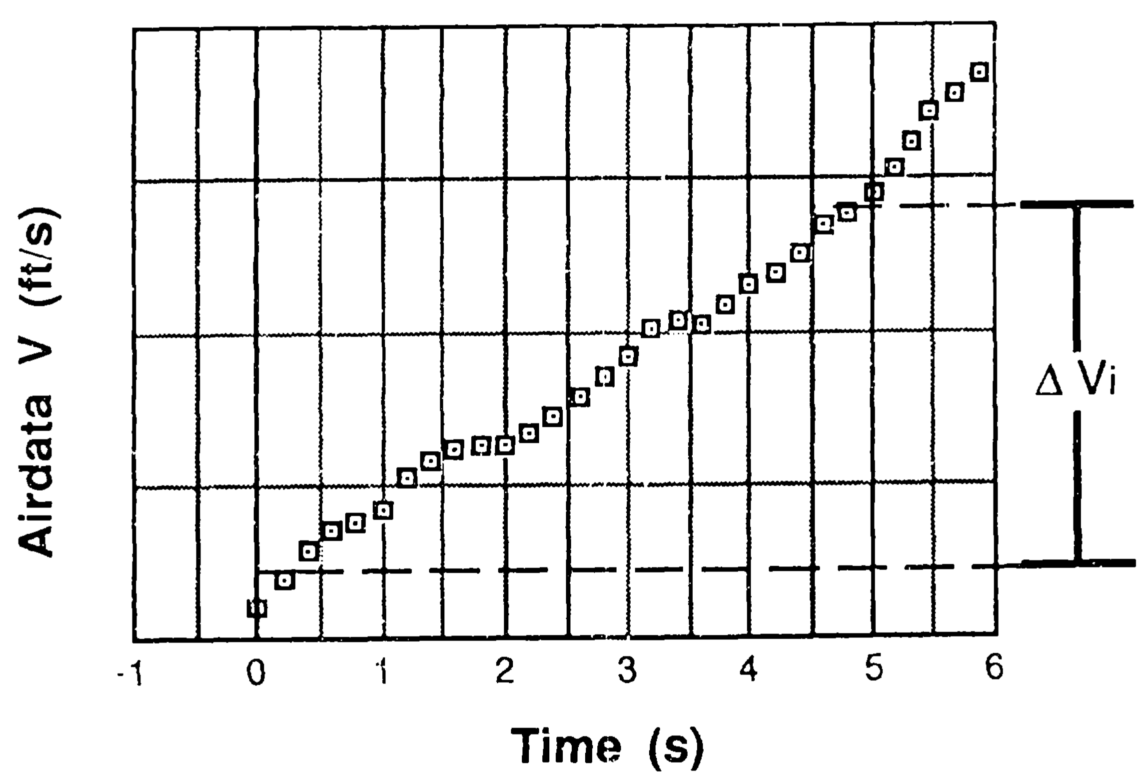
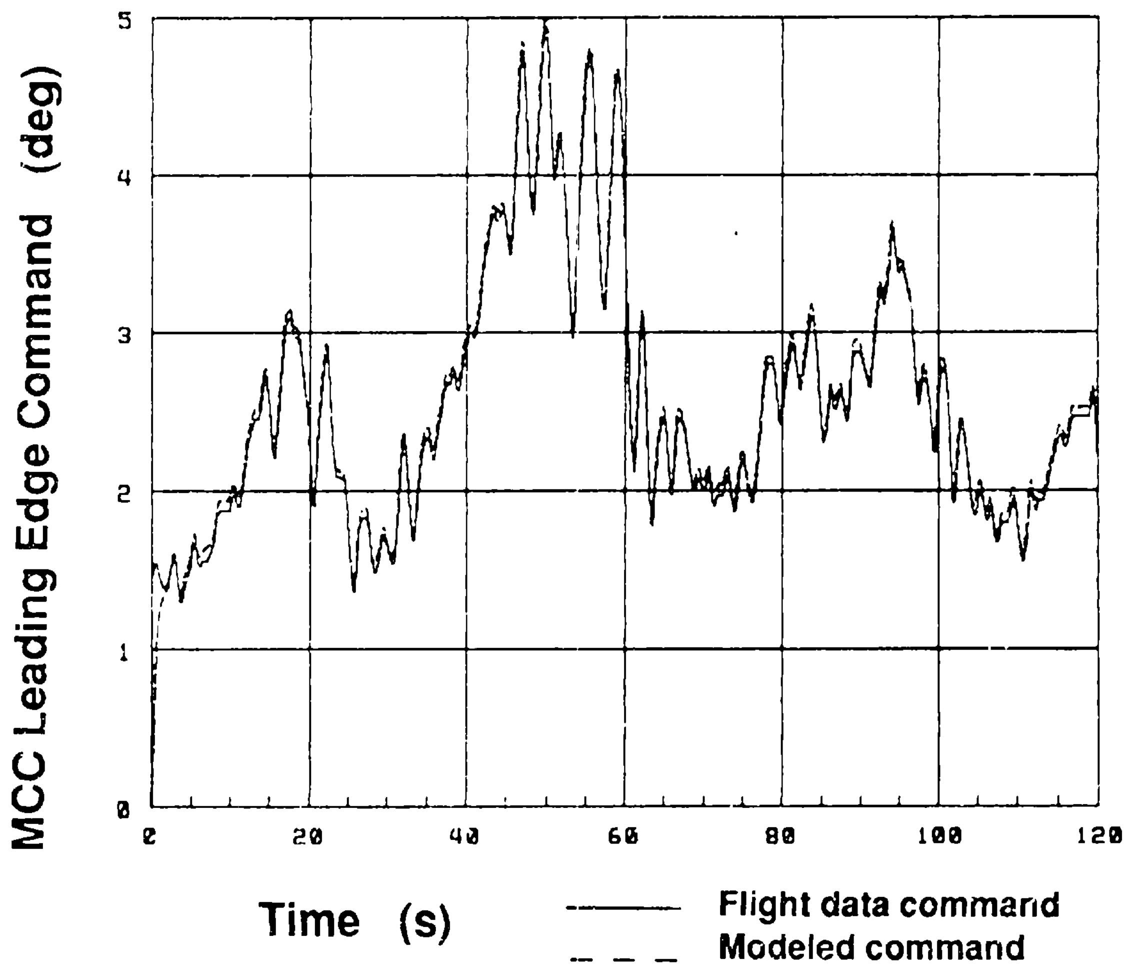
# PROPOSED CCC MODE MODIFICATION



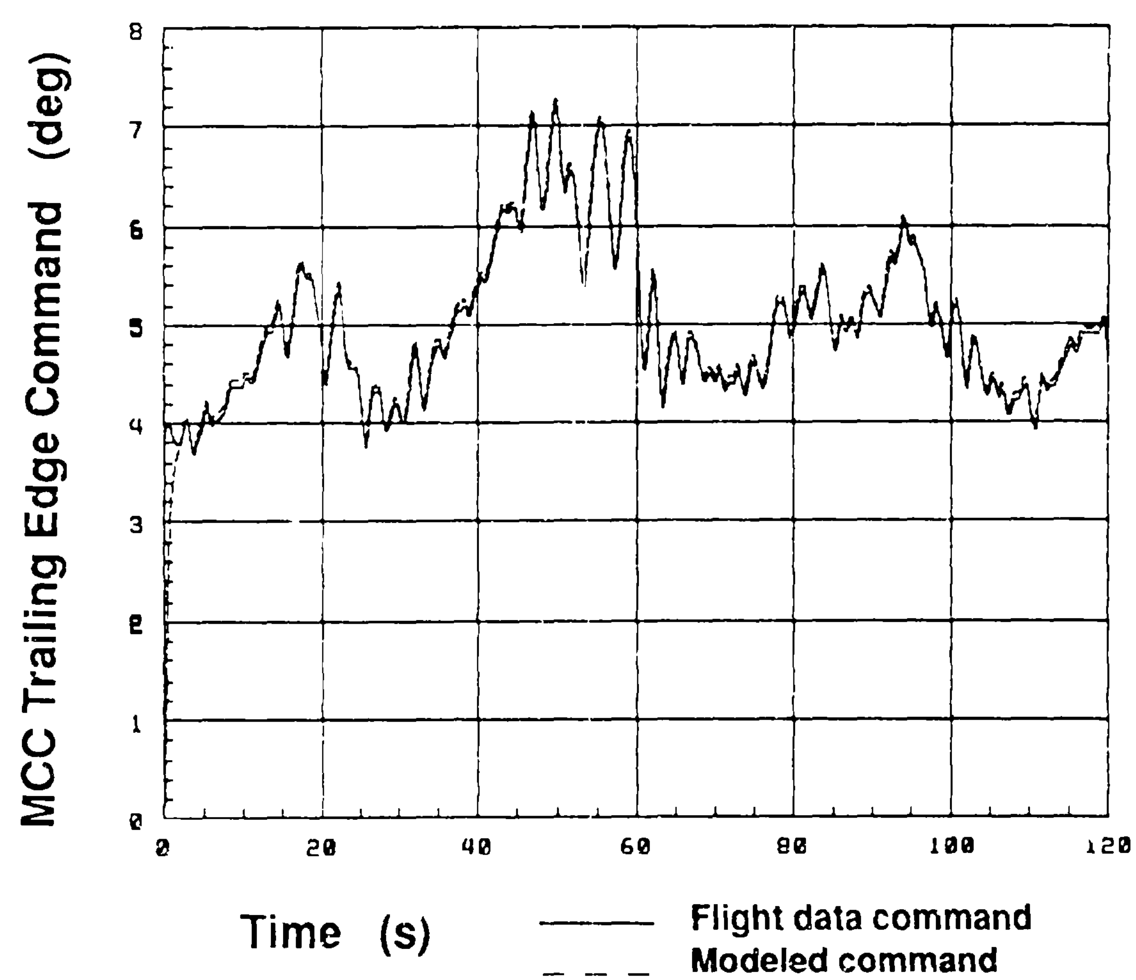
## MANEUVER CAMBER CONTROL

- Provides $(L/D)_{max}$ at steady state or maneuvering flight
- Continuously position L.E. and T.E. surfaces

## MCC LEADING EDGE COMMAND COMPARISON



# MCC TRAILING EDGE COMMAND COMPARISON



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*BRIEFING TO INDUSTRY*

## MANEUVER ENHANCEMENT/GUST ALLEVIATION

- Enhances pitch maneuvering capability
- Alleviates effects of turbulence on flight crew
- Continuously positions L.E. , T.E. surfaces and Stab.

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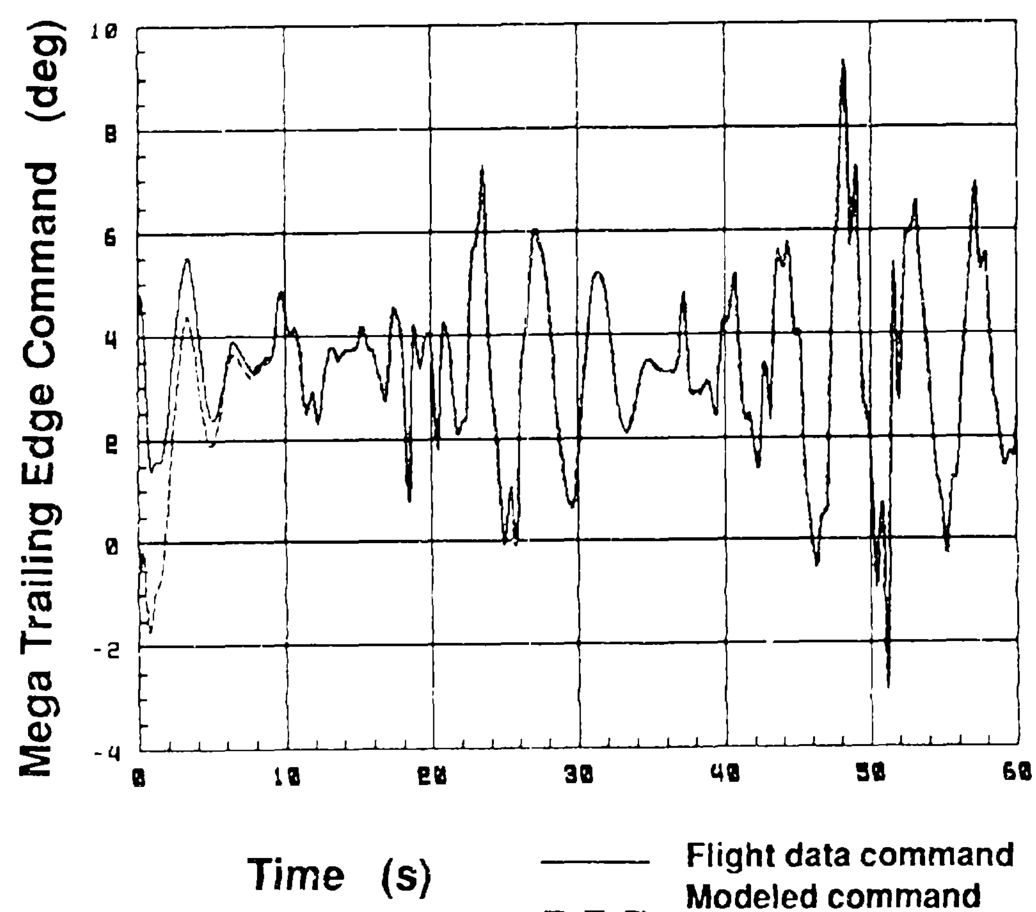
BRIEFING TO INDUSTRY

# MEGA TRAILING EDGE COMMAND COMPARISON



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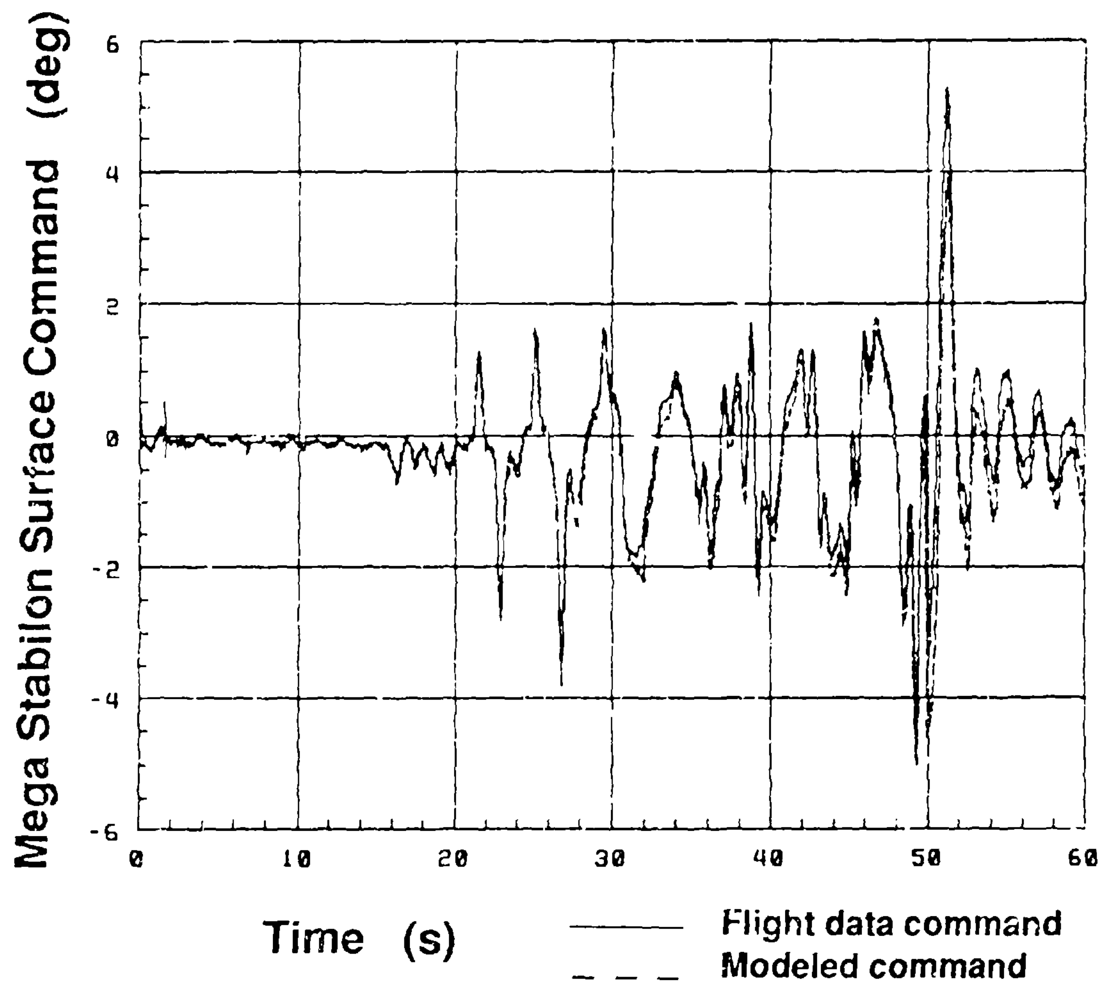
## MEGA STABILON COMMAND COMPARISON



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## AUTO MODES MODELING RESULTS

- Automatic Modes independently verified
- Provided convenient method for mode analysis
  - internal variables
- Facilitated proposed mode modifications

# STRUCTURES & MECHANIZATION LESSONS LEARNED

Frank D. Statkus
Boeing Advanced Systems

## Structures

# Lessons Learned

* Wing box

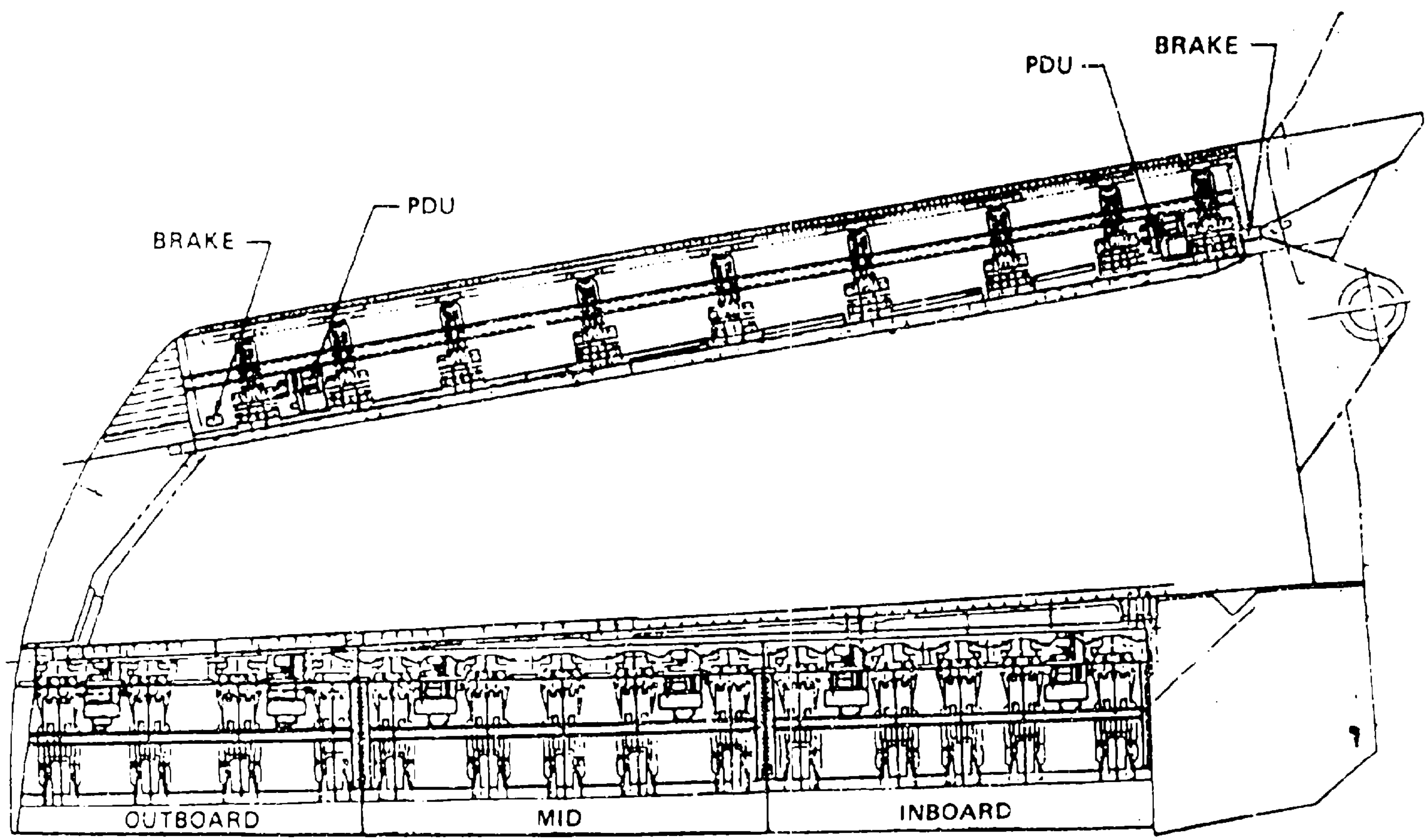
  * Design in parallel with flaps
    * Direct load paths
    * Eliminate auxiliary spar
    * Bending and torsion strength consistent with flaps
    * Wing thickness correct

  * Continuous skins leading edge to trailing edge possible for upper surface

AFTI.02

AFTI-009

# Variable Camber Wing System



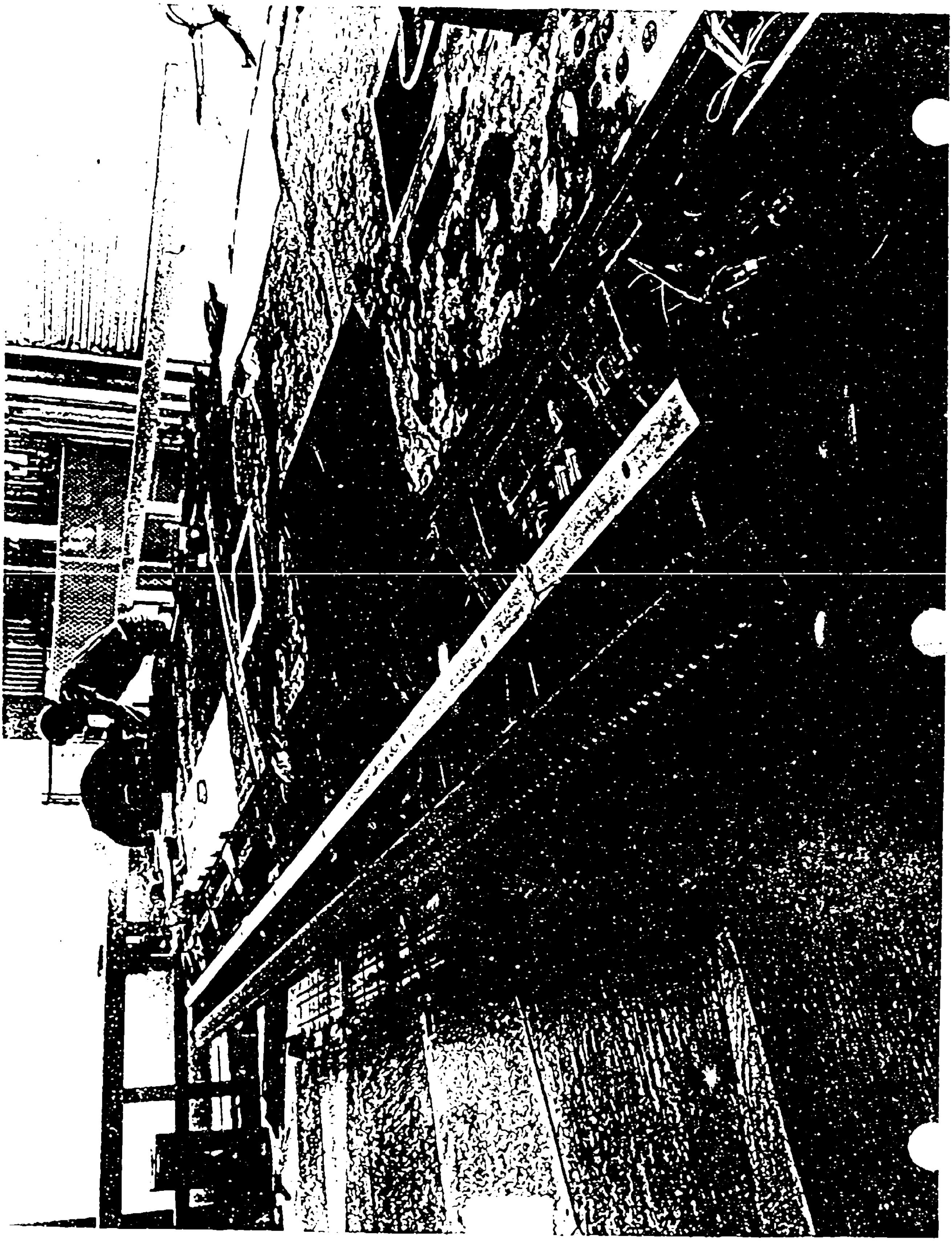
## Structures

# Lessons Learned (Continued)

* Continuous leading edge flaps

    * Fiberglass skins give structural compliance during wing bending with flap deflection

AFTI.03



Structures

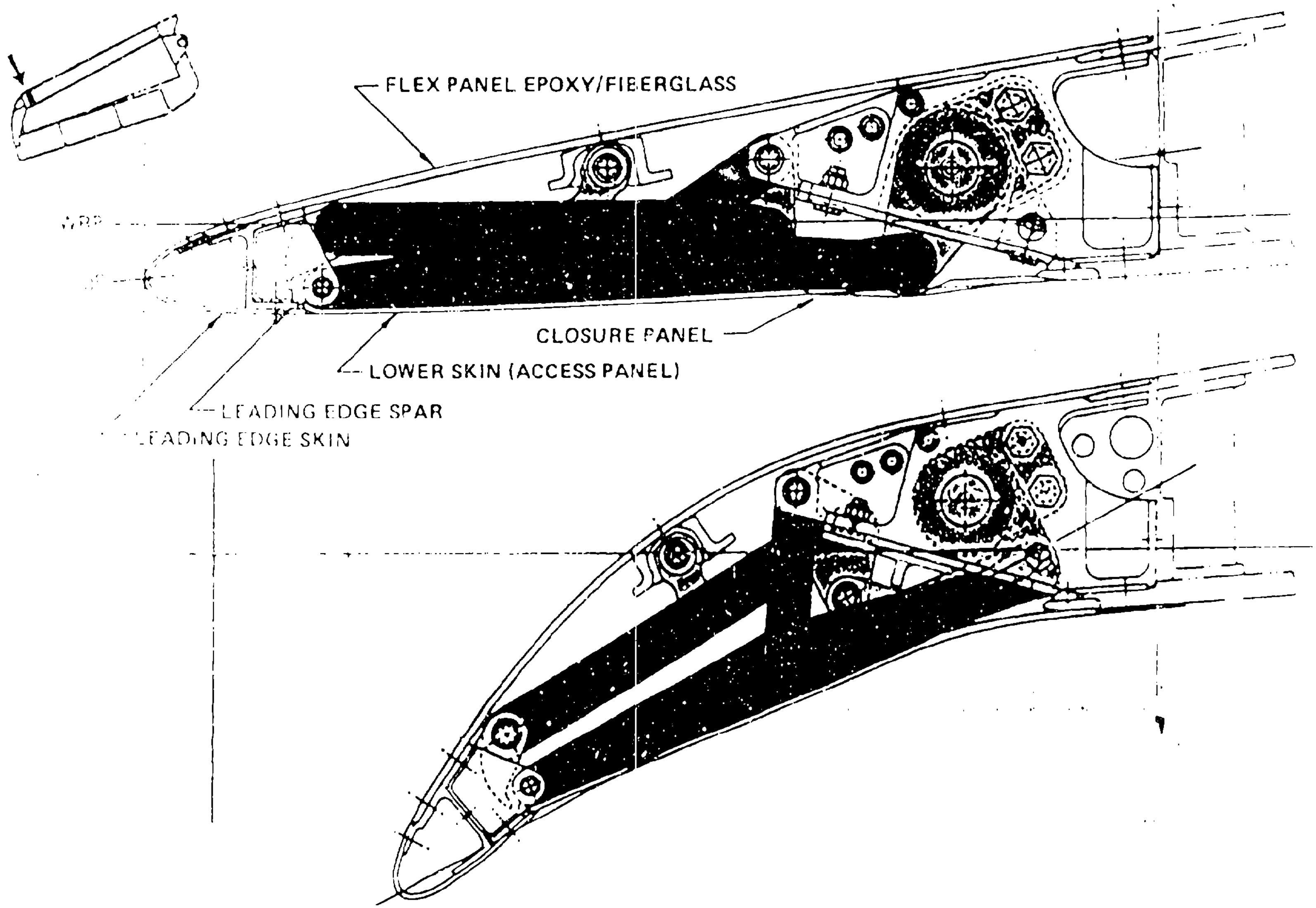
# Lessons Learned (Continued)

* Variable camber linkage

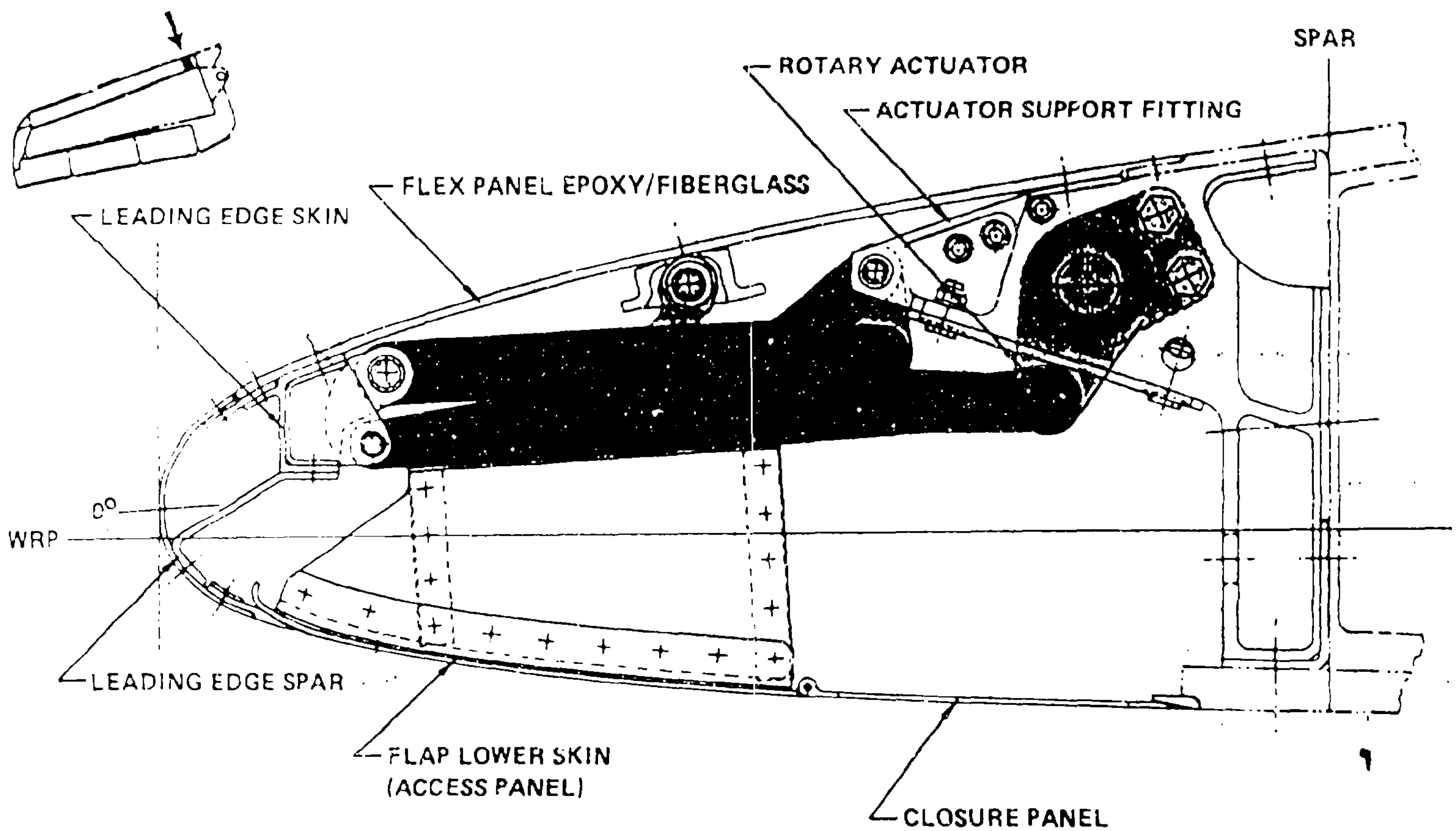
  * Single load path possible for decreased weight
  * Linkage is common for varying wing thickness
  * Linkage ratio is variable at the expense of flap rate
  * Common linkage is possible for both leading and trailing edge flaps

AFTI.04

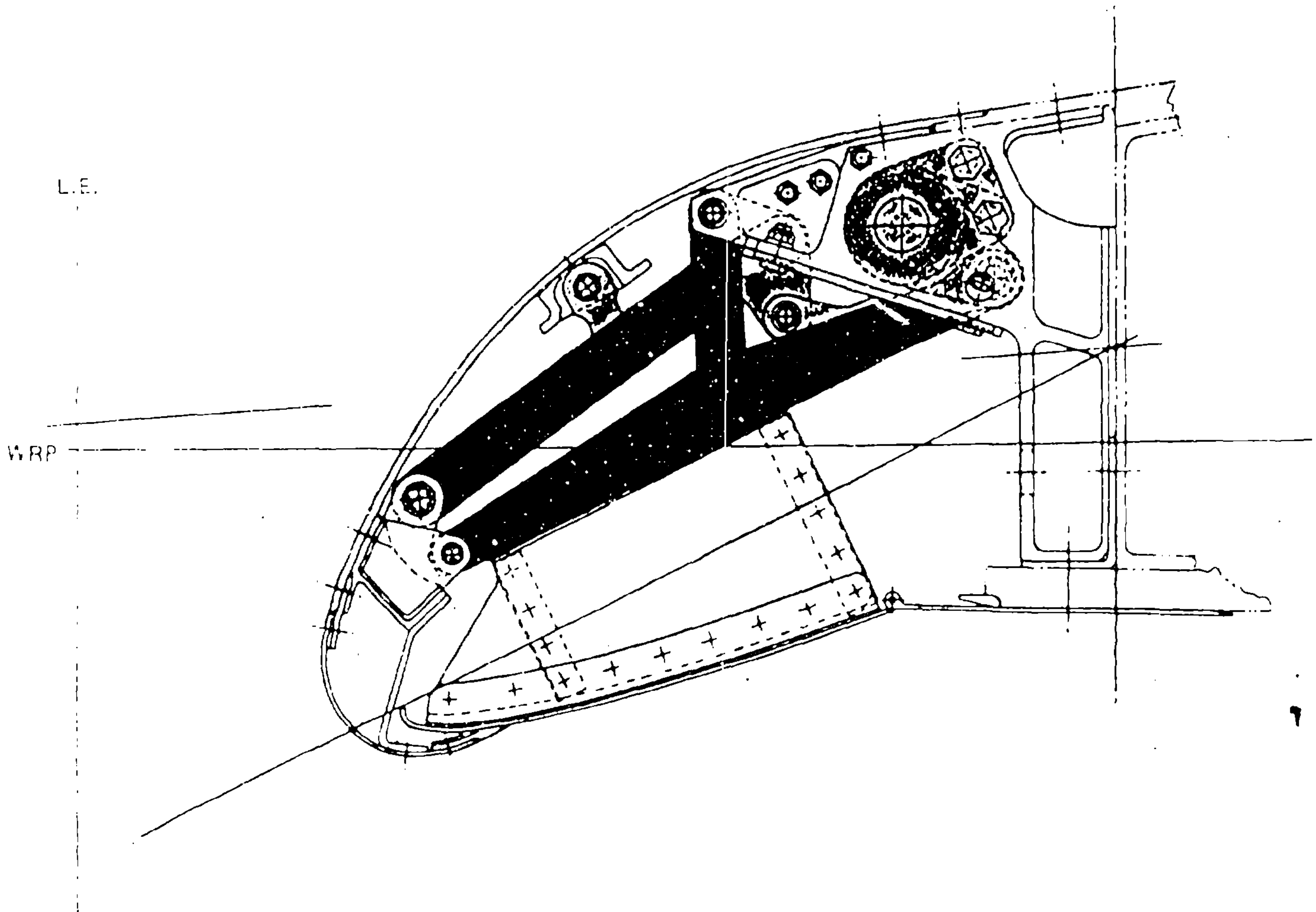
# Outboard L.E. Linkage Undeflected



# Inboard L.E. Linkage Undeflected



# Inboard L.E. Fully Deflected



## Structures

# Lessons Learned (Continued)

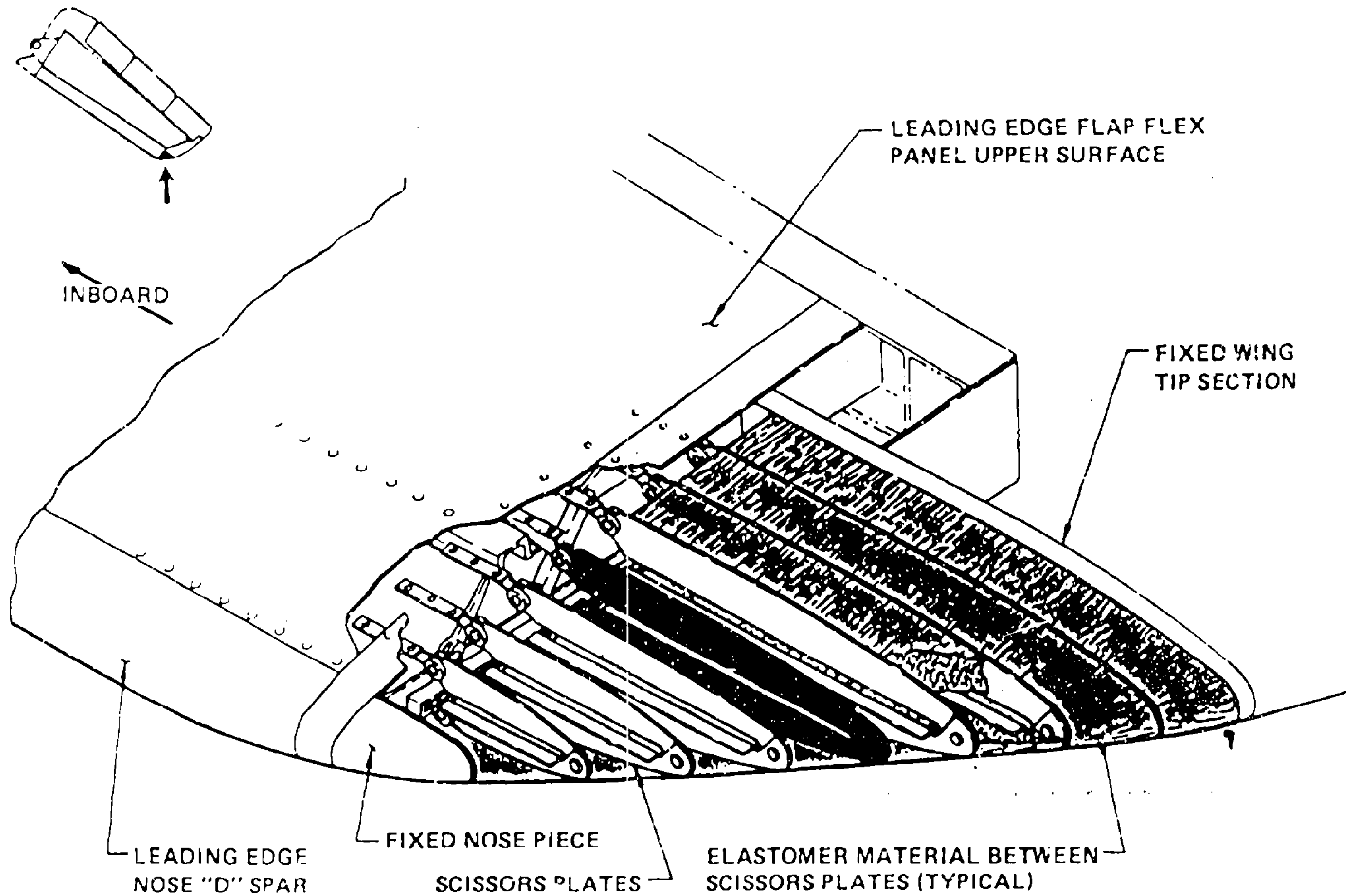
* Fixed wing design

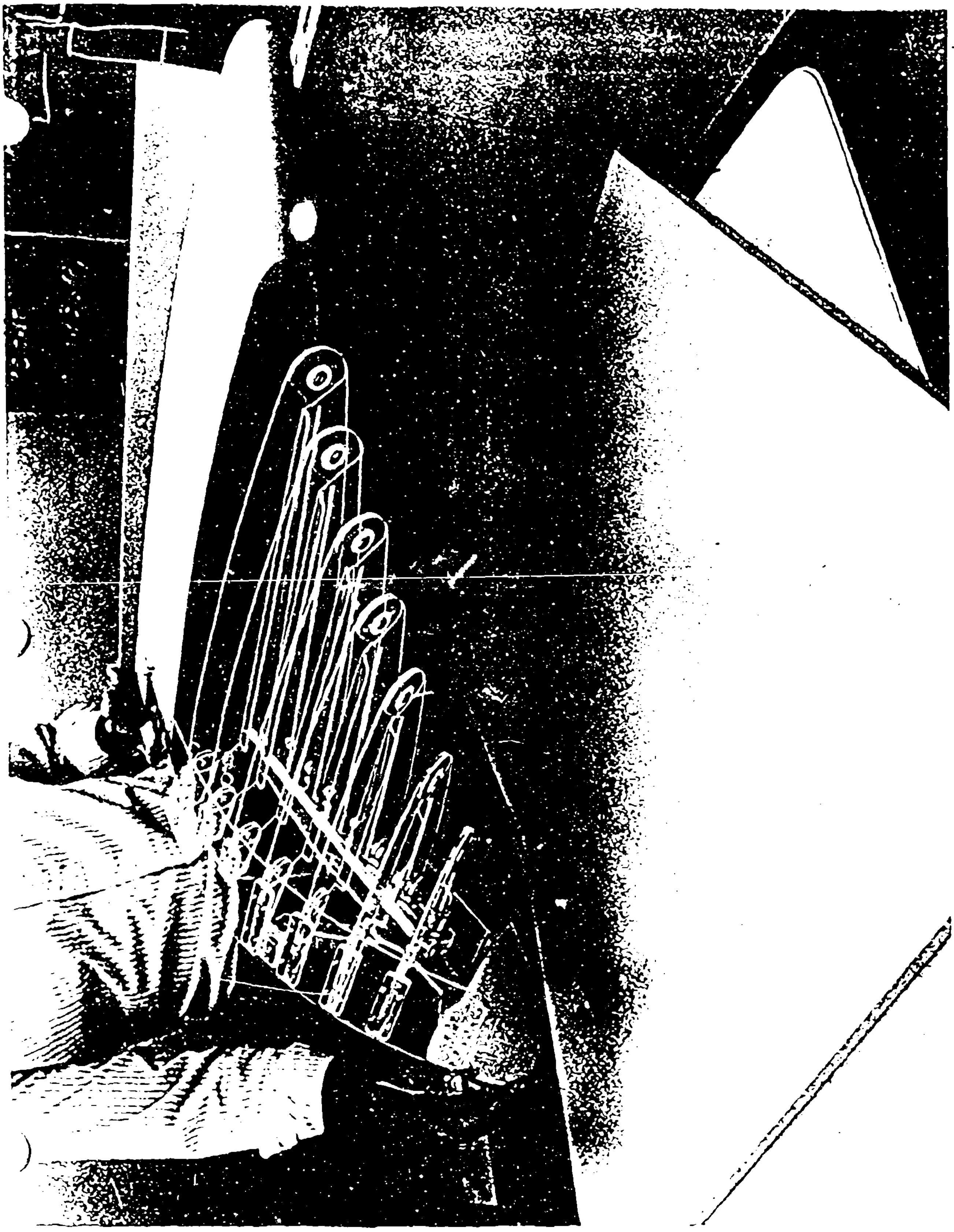
  * Eliminates flexible wing pivot seals
  * No inboard flap lockout requirements
  * No flap contour limitations for side-of-body glove matching
  * No flexible wing tip requirements
  * No flap end seals

AFTI.05

AFT1-020

# Variable Camber Leading Edge Wing Tip





## Structures

# Lessons Learned (Continued)

* Structural flap stops
  * No extruded hard stops required
  * PDU blocking mode combined with electrical brakes are sufficient to contain flap

AFTI.06

## Mechanical

# Lessons Learned

* Rotary actuators
  * Suitable solution for Maw drive system
  * Can be used to "clock" linkage along flap span to "dial in" the design wing twist
  * Wing twist can be varied by changing the actuator "clocking"
  * Flap rerigging is not required following actuator removal and replacement

AFTI.07

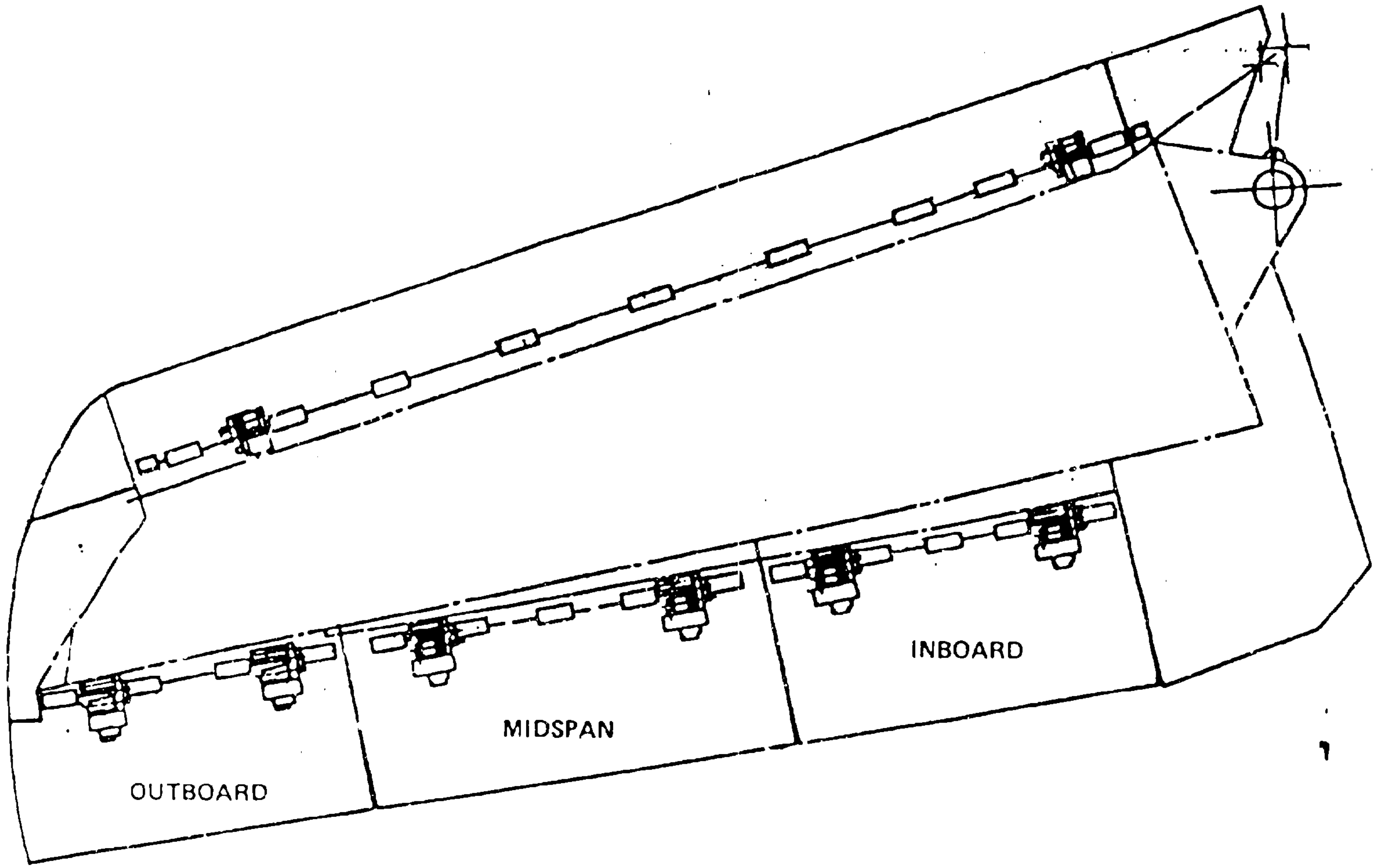
## Mechanical

# Lessons Learned (Continued)

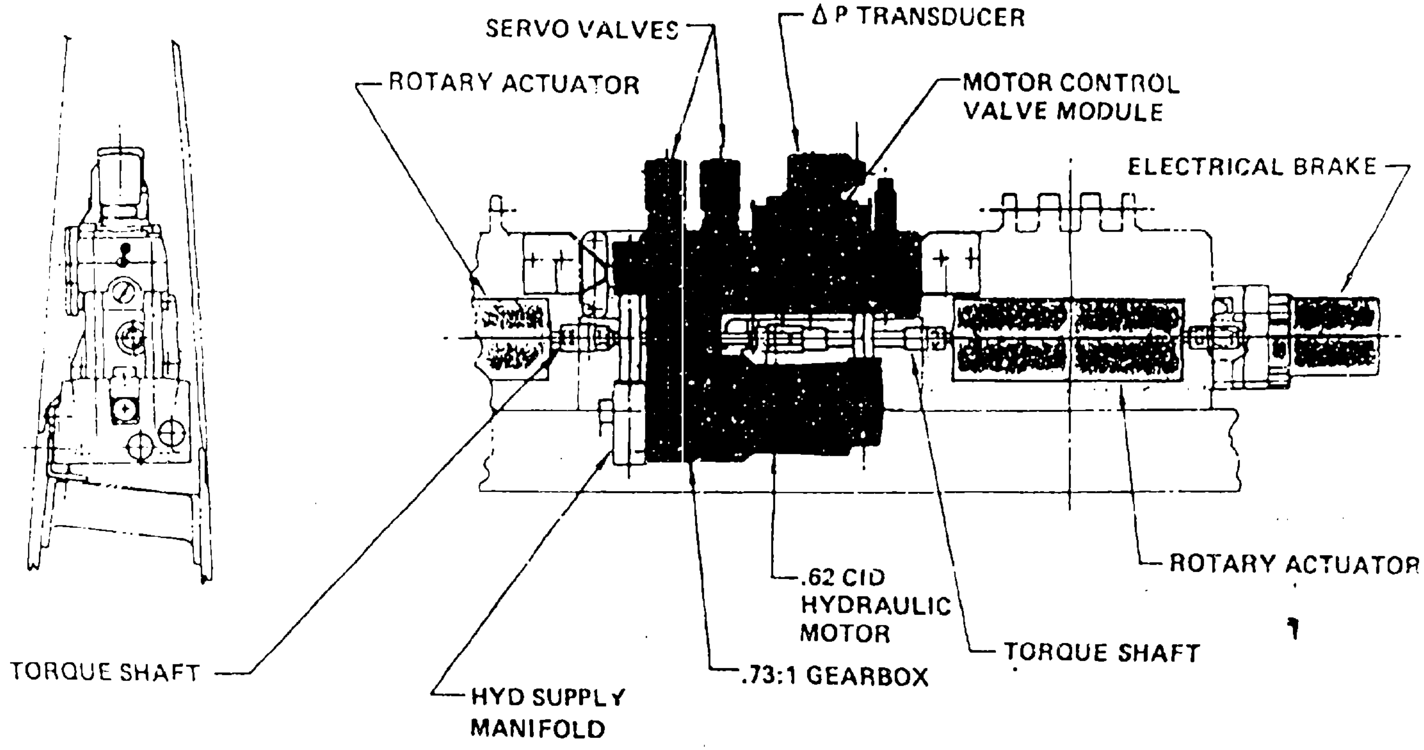
* Power drive units
  * Could be simplified while maintaining hydraulic drive duality by using a differential (combining) gear box
  * Eliminate input gear box by changing rpm from PDUs

AF71.08

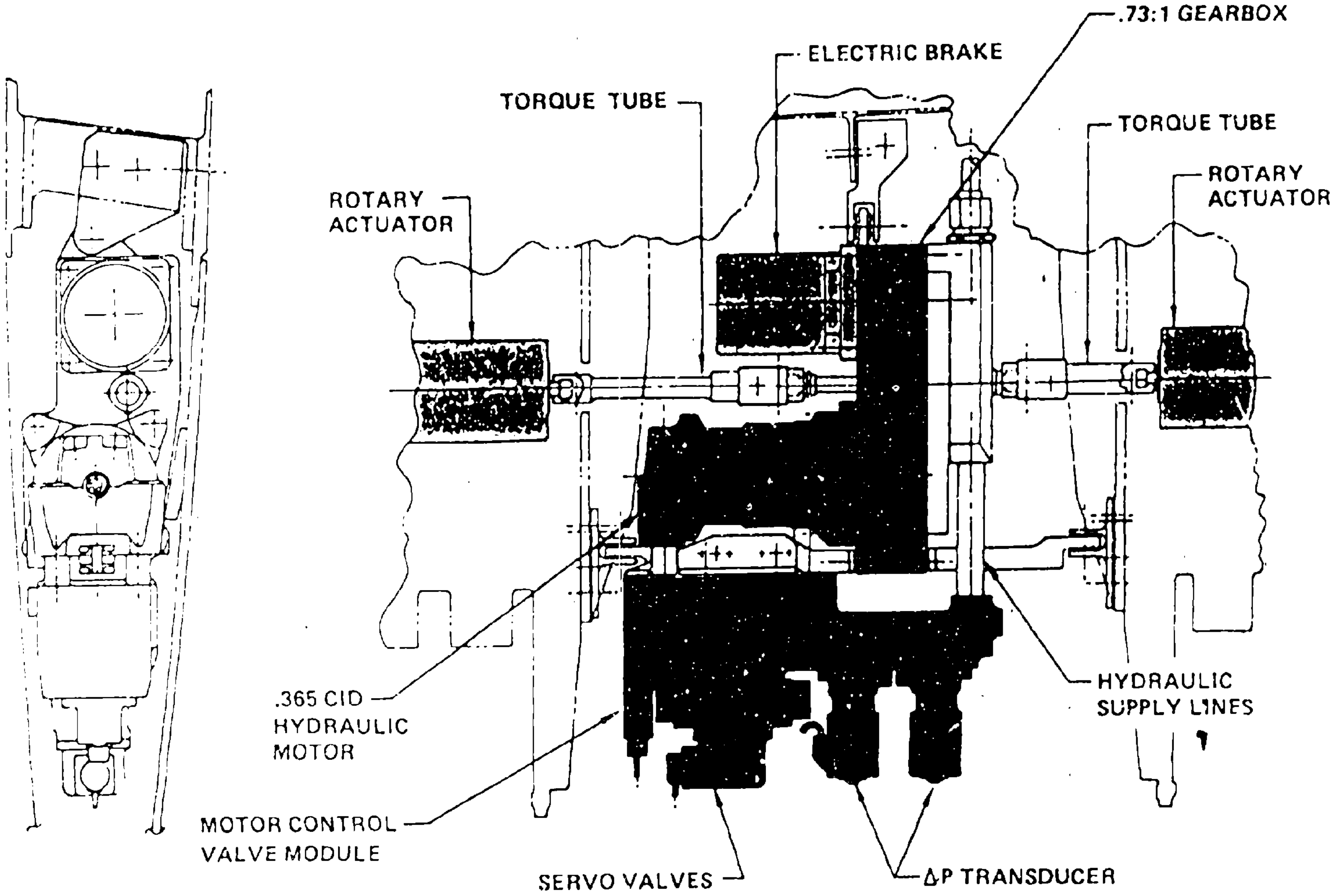
# AFTI/F-III General Arrangement Mechanical System



# L.E. Outboard Power Drive Unit



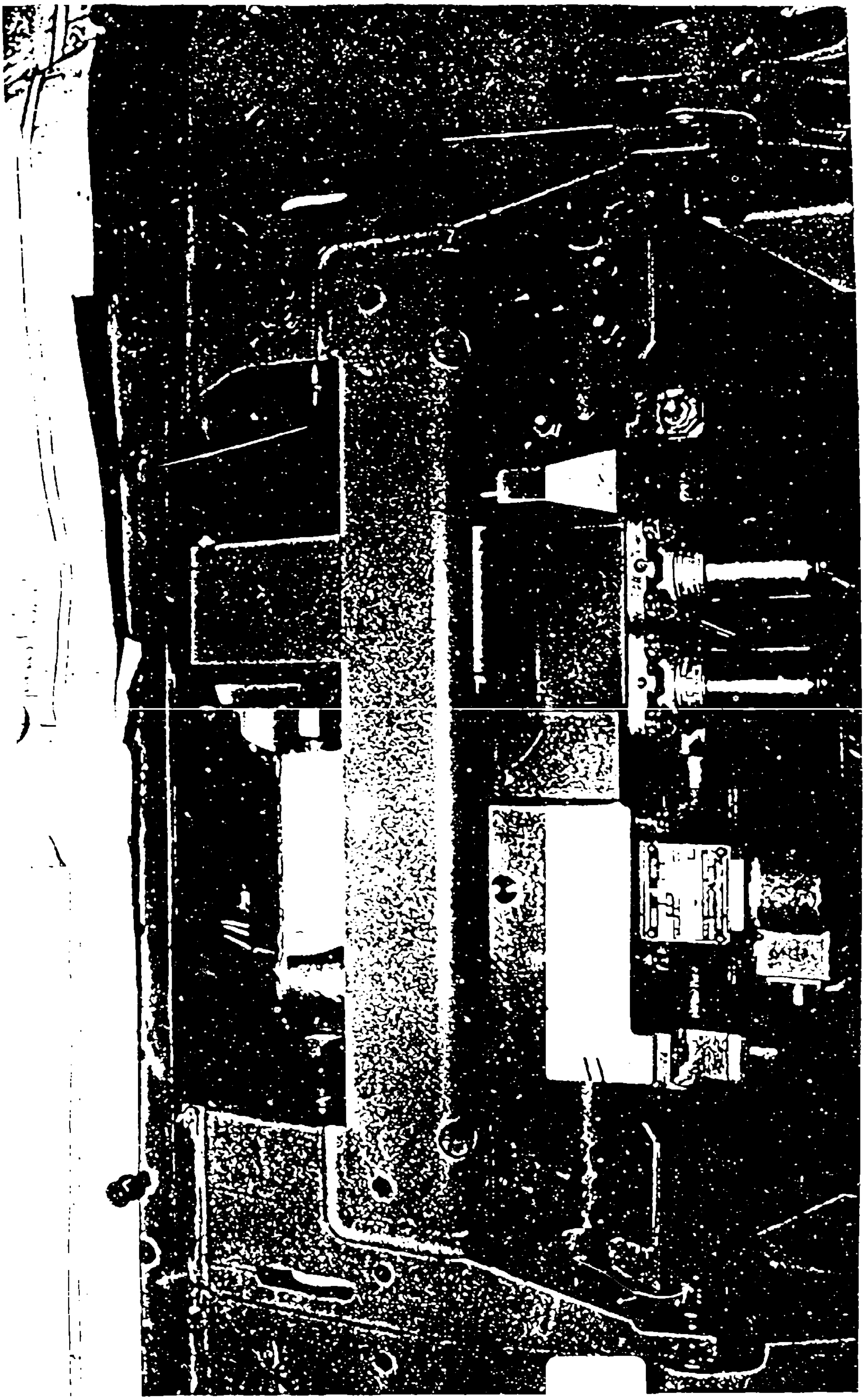
# T.E. Outboard Power Drive Unit



# Structural Problems During Design

* Rotary actuators
  * Because of long lead time:
    - Early source selection
    - Nonoptimum "off the shelf" hardware
  * Increased trailing edge flap rates (control requirements)
    - Significantly shortened actuator life
    - Ultimate strength integrity not affected
* Wing box
  * Higher than expected stress levels required unplanned strengthening of wing box
* Trailing edge envelope:
  * Thin outboard trailing edge and increased flap rates reduced mechanical advantage of linkage mechanism forcing major redesign

AFTI.09



# Flight Test Results

* Flex panels and mechanism
  * Good correlation of flight test stress data with predicted stress levels; no problems
* Pivot fitting
  * Higher than predicted stress levels
  * Probable cause: Manner in which torsion is reacted
  * Possible restrictions of flight envelope
* Power drive unit quill shaft
  * Early fatigue failure
  * Cause
    - Consistent overload due to too severe preflight and quality testing
    - Tool marks
  * Remedial action
    - Software change reduced dynamic factor during preflight test
    - Improved surface finish ~ $\overset{32}{\checkmark}$

AFTI.10

# FLIGHT CONTROL SYSTEMS LESSONS LEARNED

Joseph M. Hall
Boeing Advanced Systems

# FLIGHT CONTROL SYSTEM LESSONS LEARNED

I IN SOFTWARE DEVELOPMENT / TESTING

II ON THE FLIGHT SIMULATOR

III IN FLIGHT TEST

# LESSONS LEARNED
# IN SOFTWARE DEVELOPMENT / TESTING

I IN INITIAL SOFTWARE DEVELOPMENT, CONSIDERATION NEEDS TO BE GIVEN TO EASE OF TESTING

- WRITE DETAILED LOGIC EQUATIONS
- NAME ALL IMPORTANT VARIABLES
- SPECIFY FORMS OF FILTERS

II TEST SOFTWARE MUST ALSO BE TESTED

- ONLY SOFTWARE ERROR FOUND WAS IN TEST SOFTWARE

3

# LESSONS LEARNED ON THE FLIGHT SIMULATOR

I REALISTIC AND DEMANDING PILOT TASKS, USING A VISUAL SYSTEM, ARE NECESSARY FOR EVALUATION OF FLYING QUALITIES

II EARLY EVALUATION OF SIMULATOR COMPUTATIONAL DELAYS IS NECESSARY TO ASSURE VALIDITY OF RESULTS

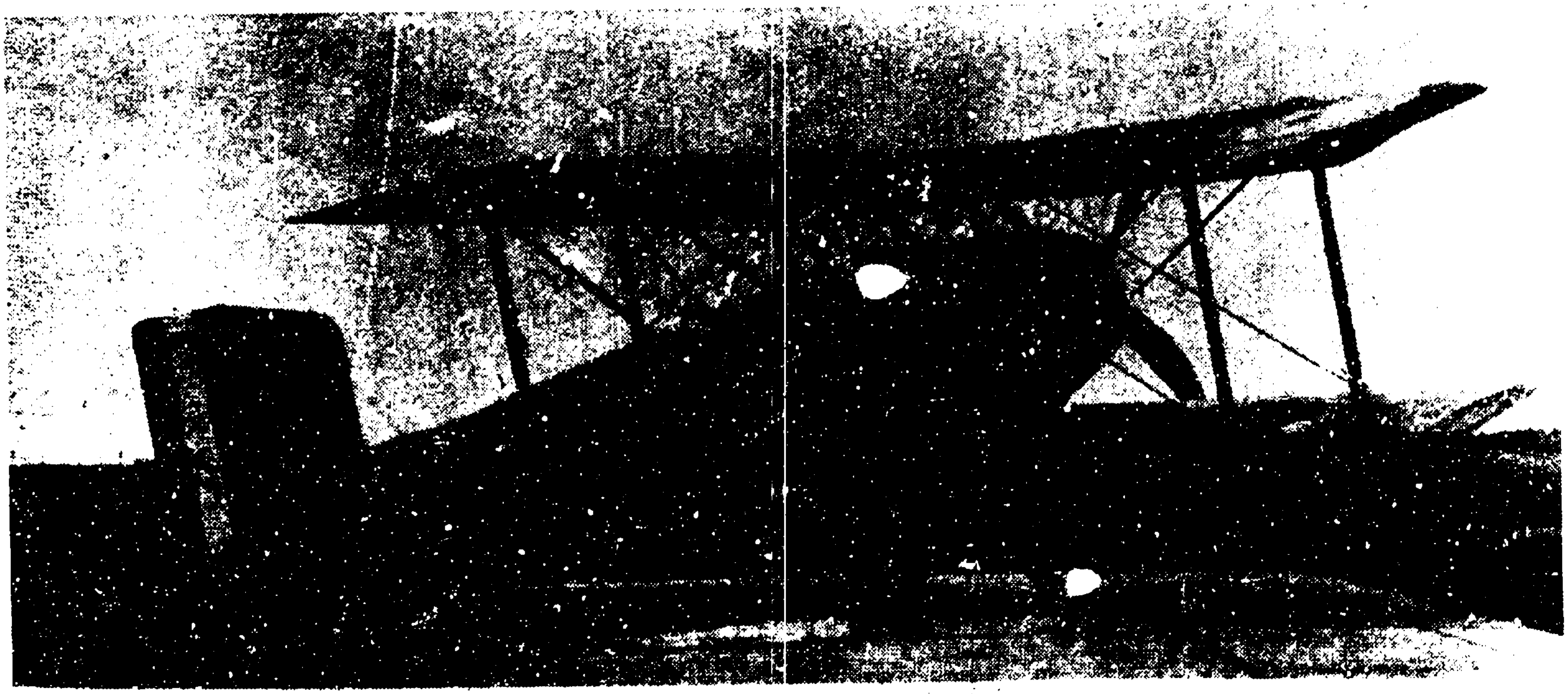
III ARRAY PROCESSORS ARE NECESSARY TO ACHIEVE ACCEPTABLE DELAYS WHEN THE AERODYNAMIC DATA BASE IS LARGE

# LESSONS LEARNED IN FLIGHT TEST

- BUILT-IN PILOT SELECTABLE FEATURES SAVE TIME
  - VARIABLE GAIN ON MEGA MODE
  - SELECTABLE FEEDBACK OF ROLL RATE IN AYC SYSTEM

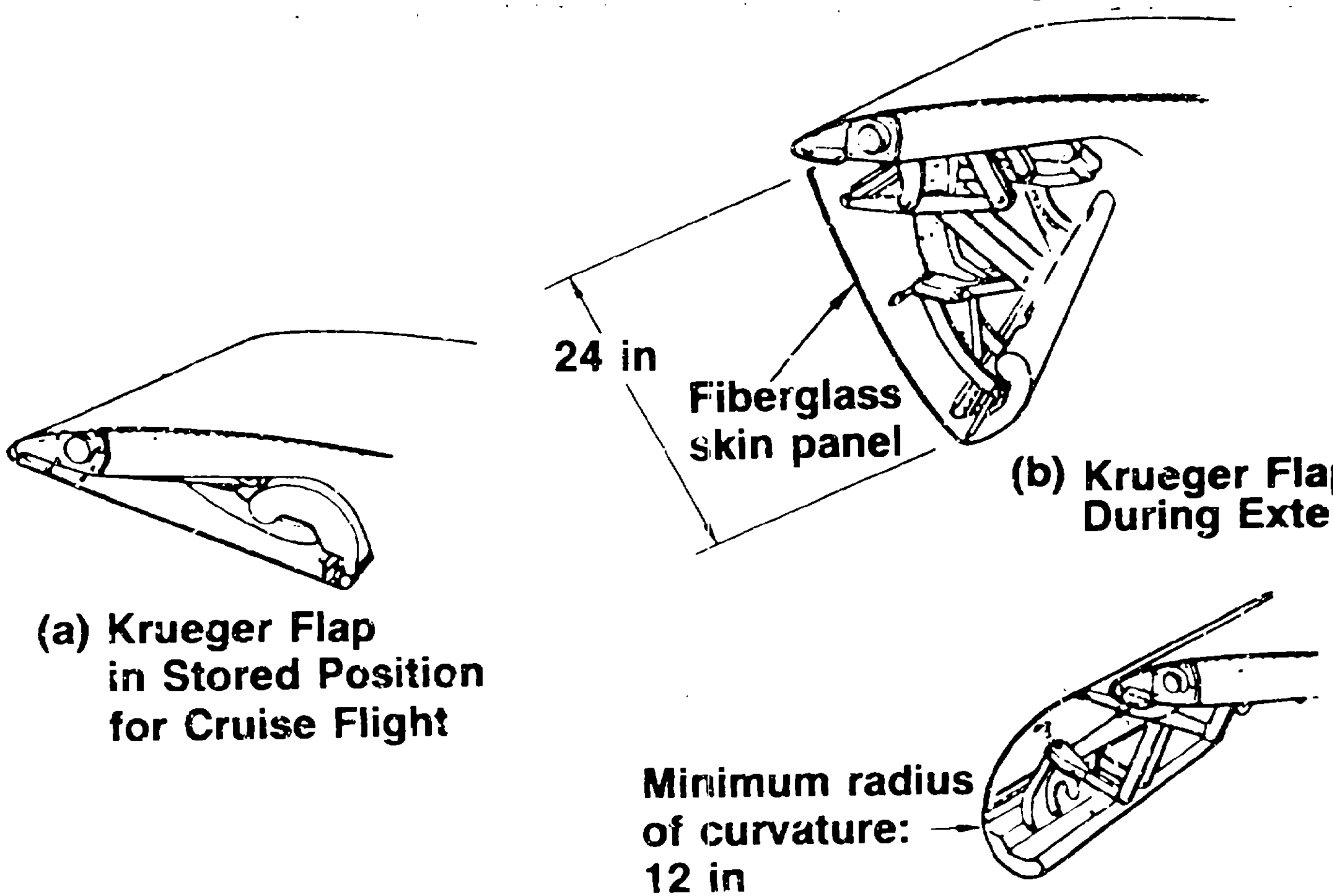
# CONSIDERATIONS FOR AN OPERATIONAL SYSTEM

Douglas K. Gould
Boeing Advanced Systems



243. Handley Page R/200 landplane, N.29.

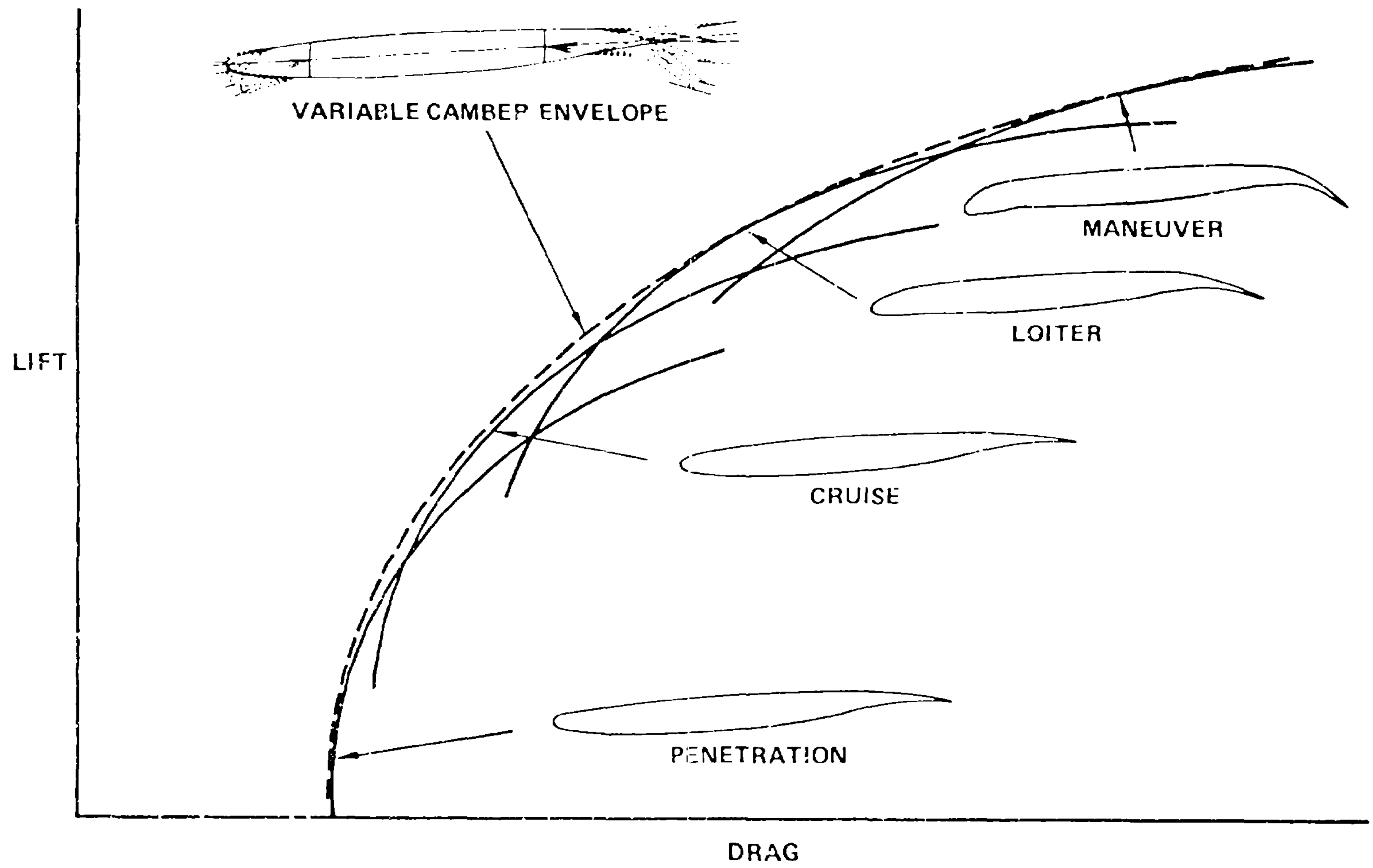
# Current Use of Flexible Skin Technology—747 Variable Camber Leading-Edge Krueger Flap



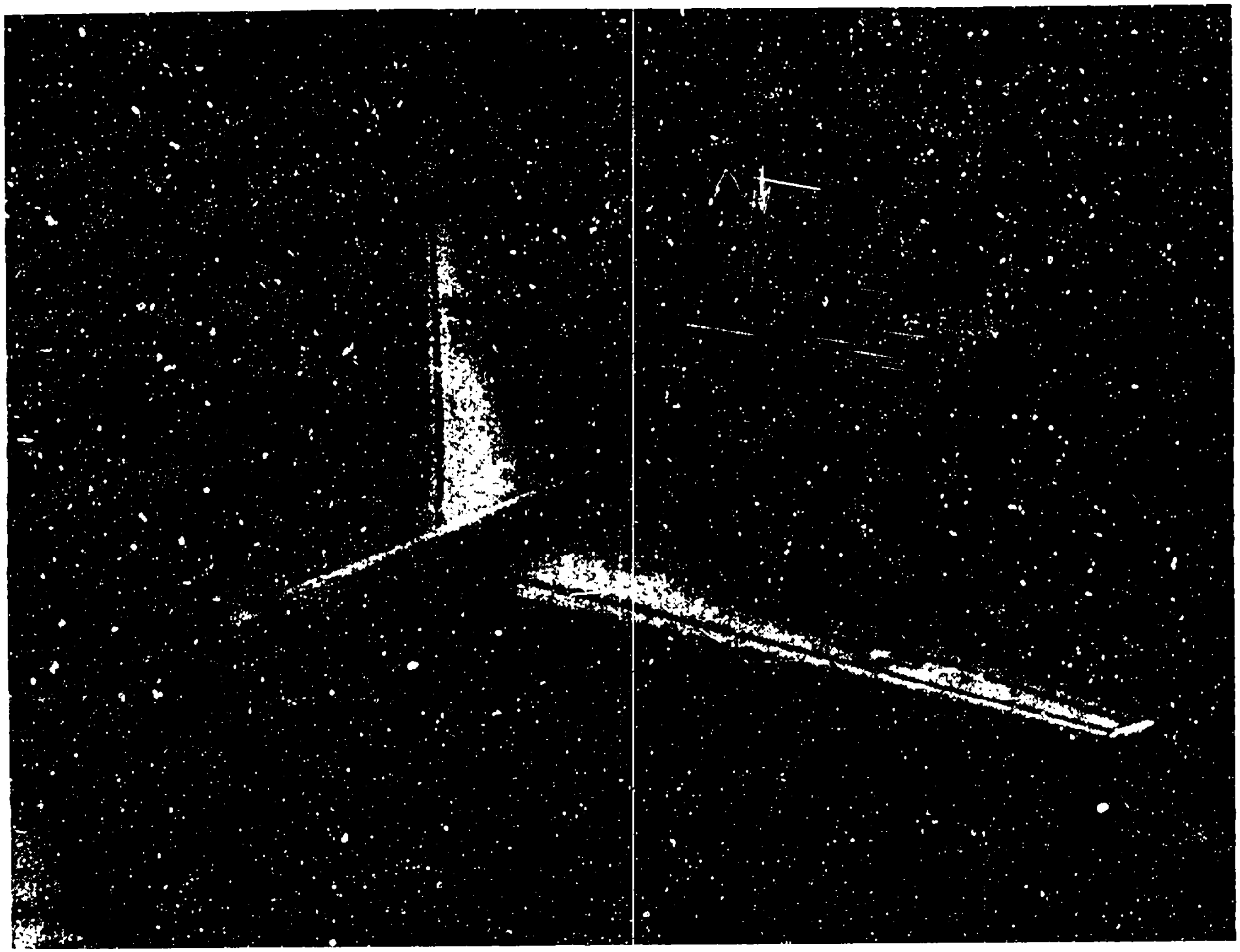

(a) Krueger Flap in Stored Position for Cruise Flight

(b) Krueger Flap During Extension

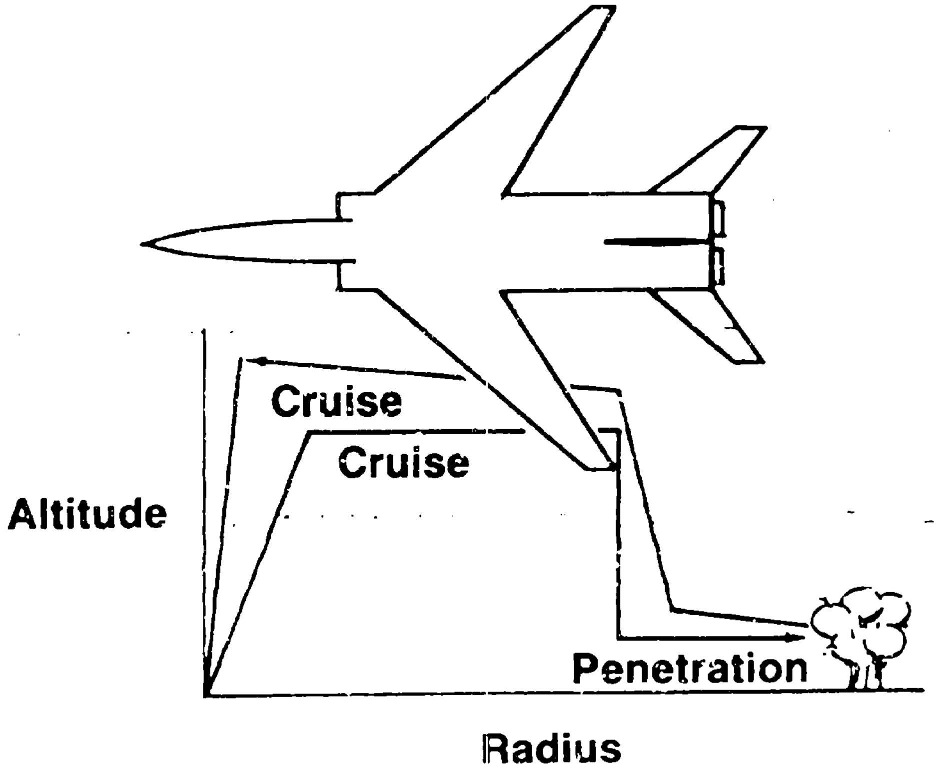
# Mission Adaptive Wing
# Aerodynamic Characteristics



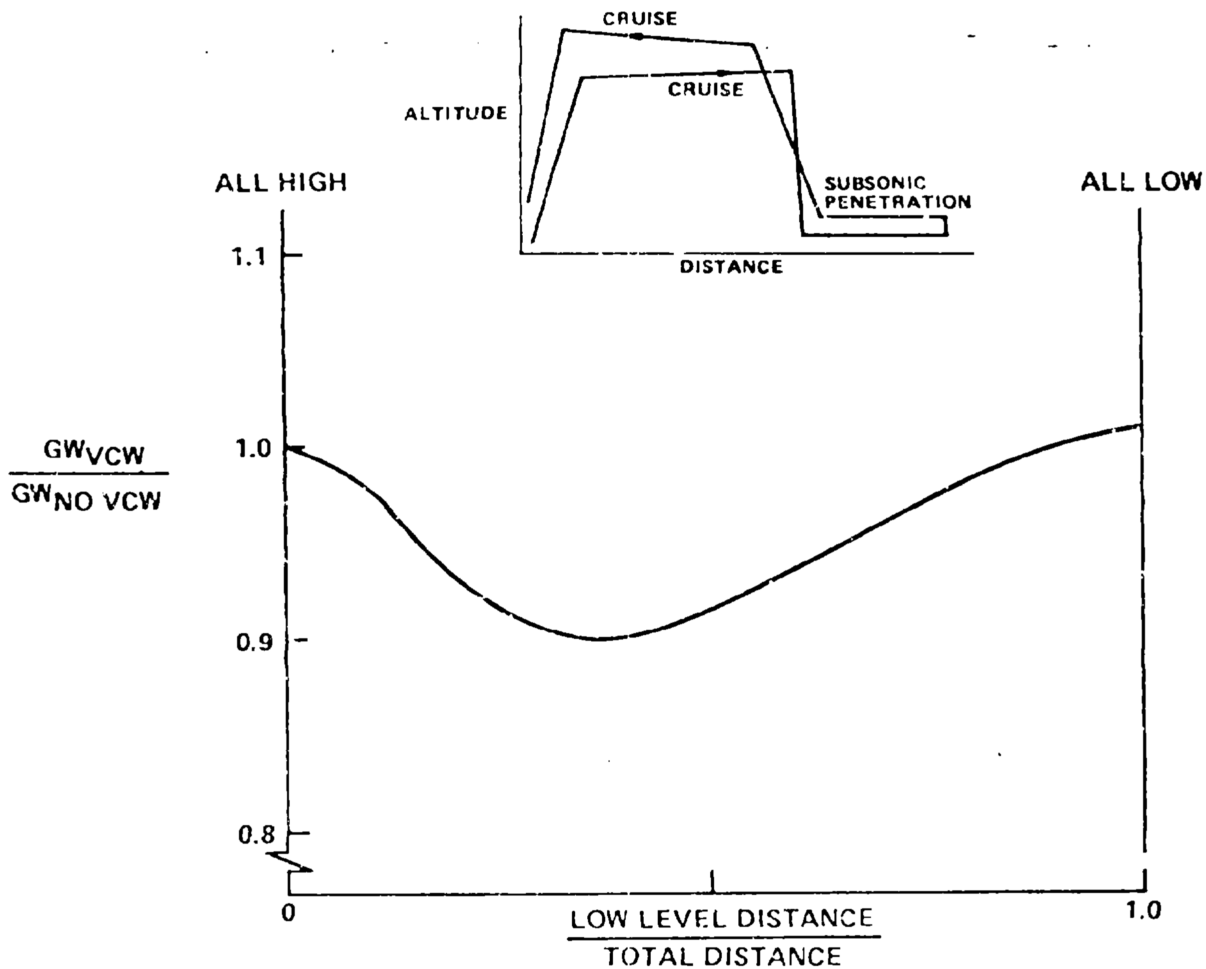
# Bomber



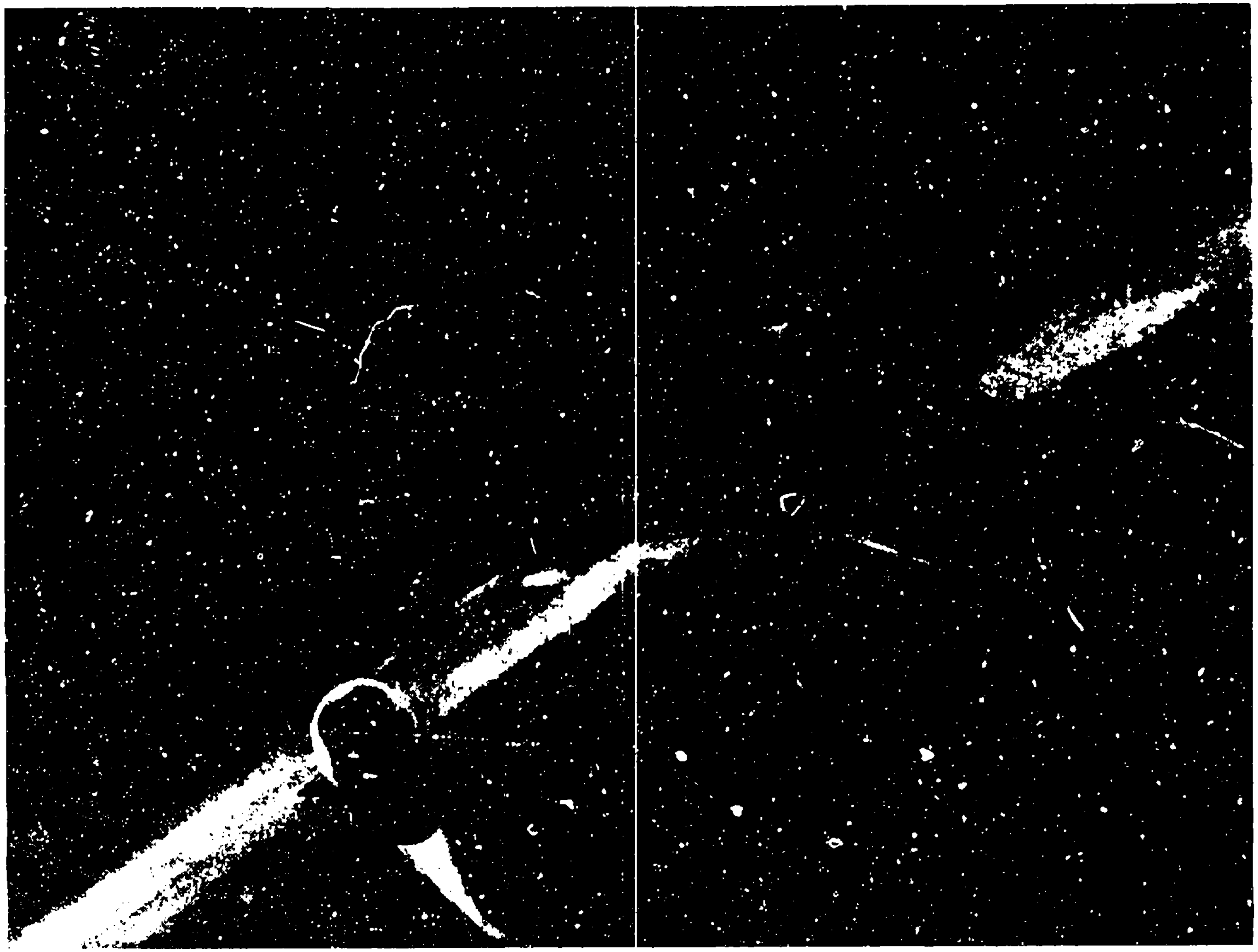
# Typical Bomber Mission



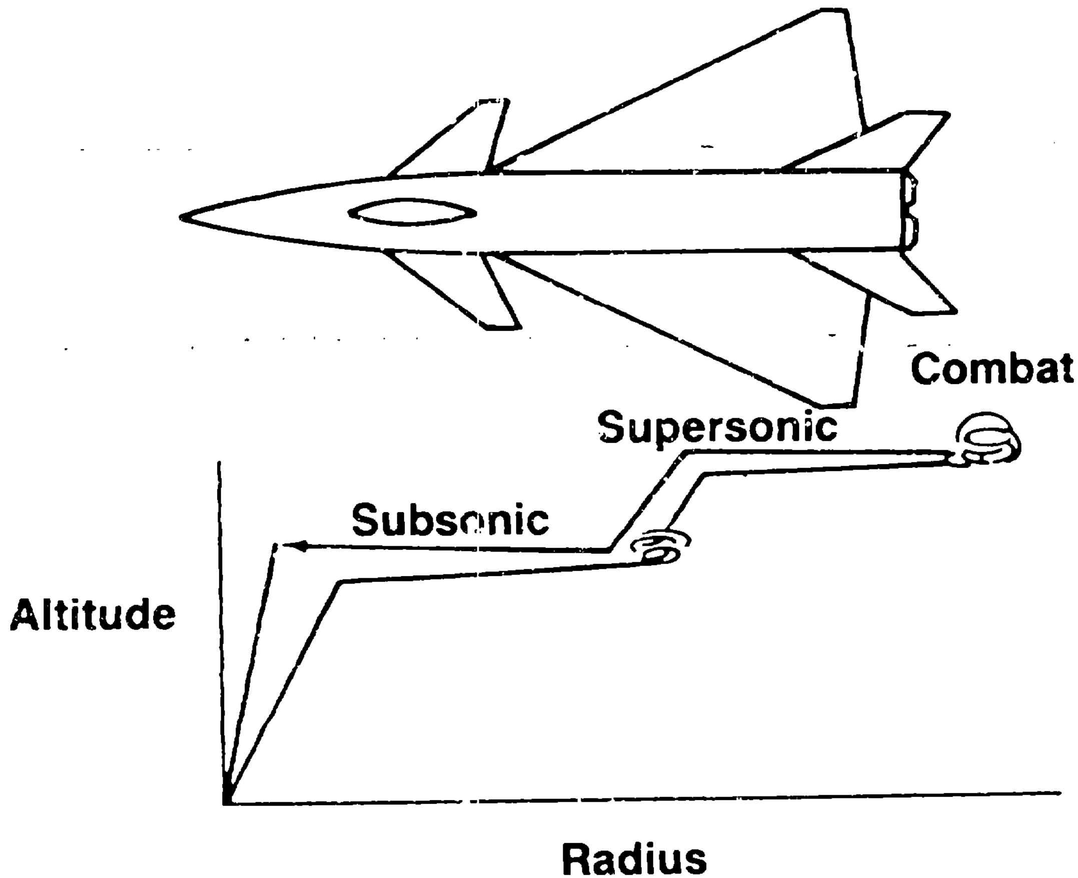
# Application of Mission Adaptive Wing Technology to Bomber



# Fighter



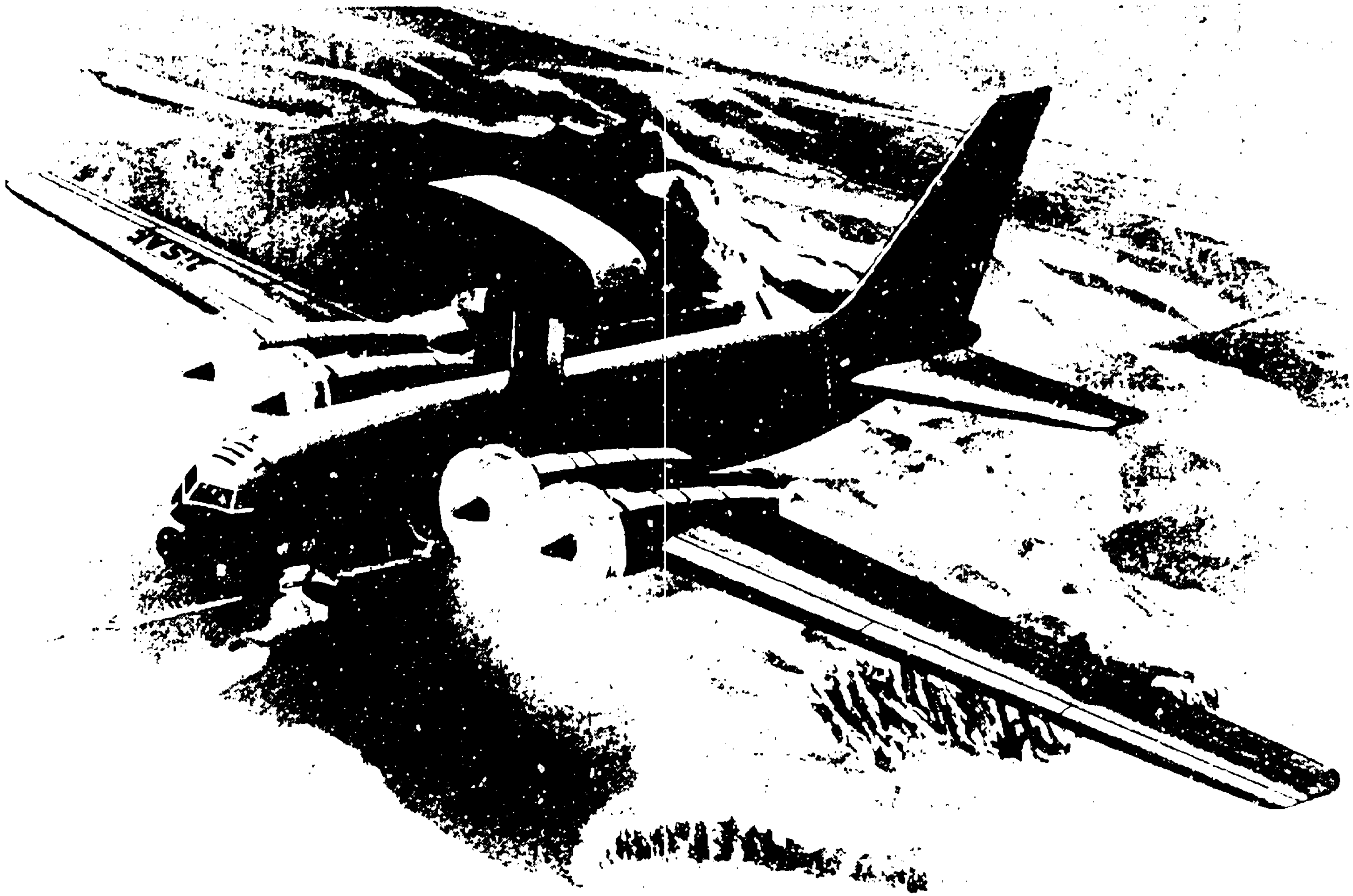
# Typical Fighter Mission



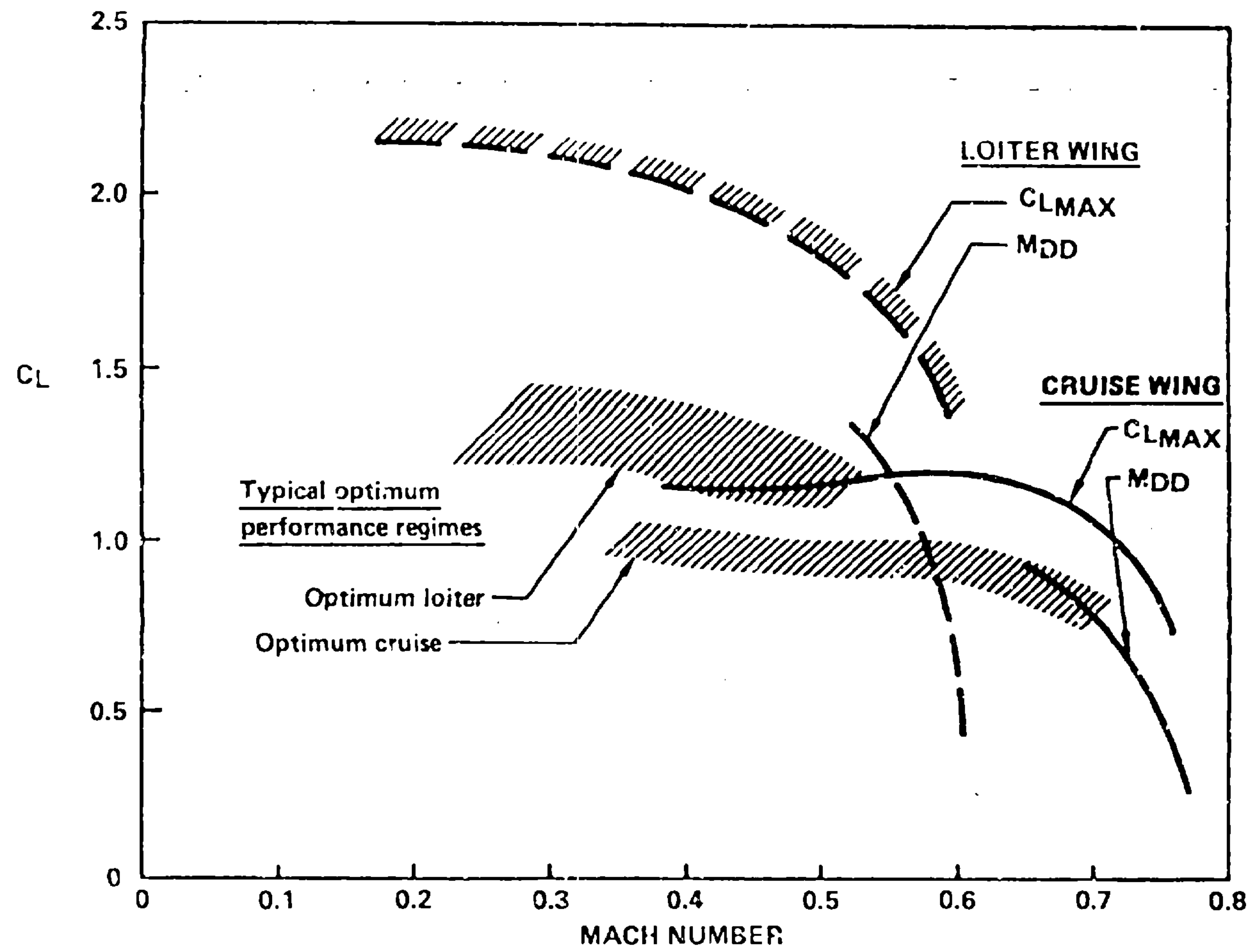
# Application of Mission Adaptive Wing Technology to Fighter

- Maneuver Camber Control to maximize lift/drag and buffet-free lift over entire flight envelope
  - 50% increase in L/D @ M = 0.9, 5 g's compared to fixed camber wing
  - 20% increase in useable lift @ M = 0.9
- Maneuver Load Control
  - Δwing weight = –100 lbs. due to reduction in wing design bending moment
- Maneuver Enhancement/Gust Allevation
  - Blended wing and tail commands for quicker maneuver
  - Gust response reduced 30%
- Cruise Camber Control
  - Optimum cruise camber for external configuration changes
    - Weapons
    - Fuel tanks
    - Control surface misalignments
    - Damage

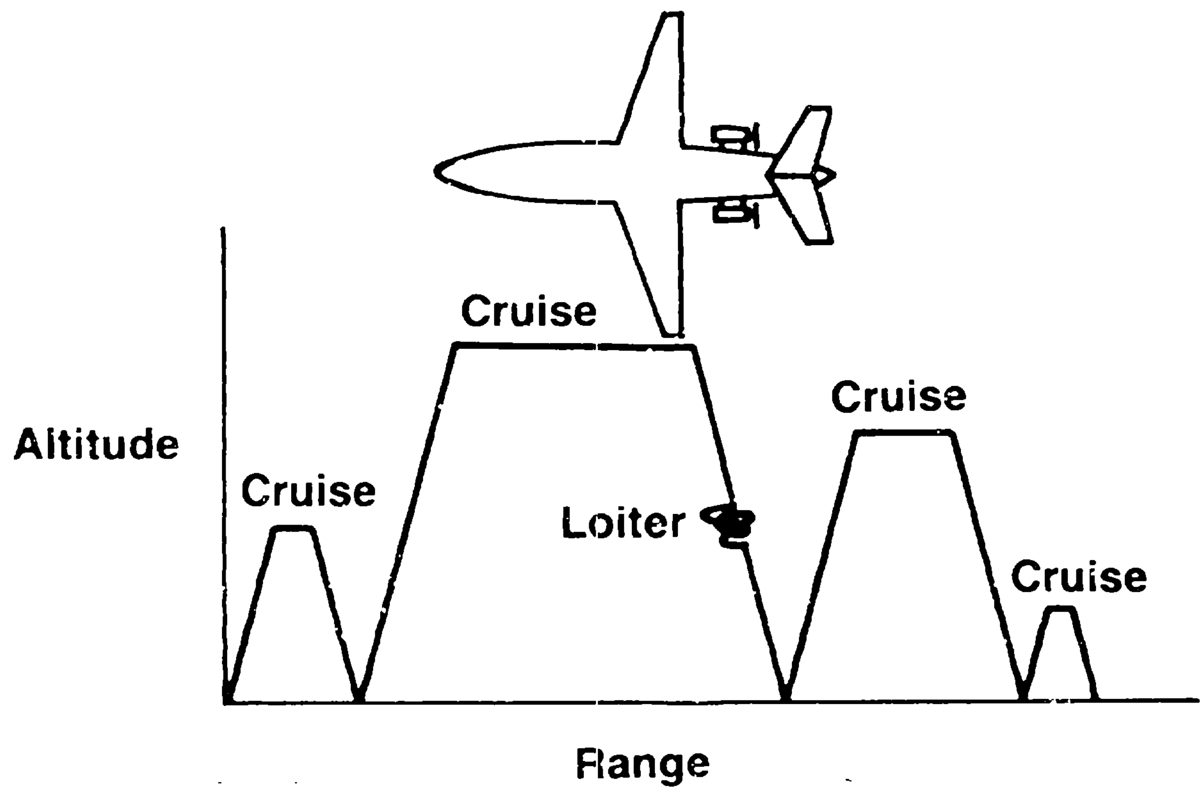
# Missileer



# Application of Mission Adaptive Wing to Missileer



# Typical Short-Haul Transport Flight



# Mission Adaptive Wing Benefits

- An increase in performance and operating capability at any off design point for a fixed geometry design

- Reduction in Design Gross Weight required to meet the performance requirements for a new aircraft

- An increase in performance for requirements not critical from a sizing standpoint

# Mission Adaptive Wing Applicability

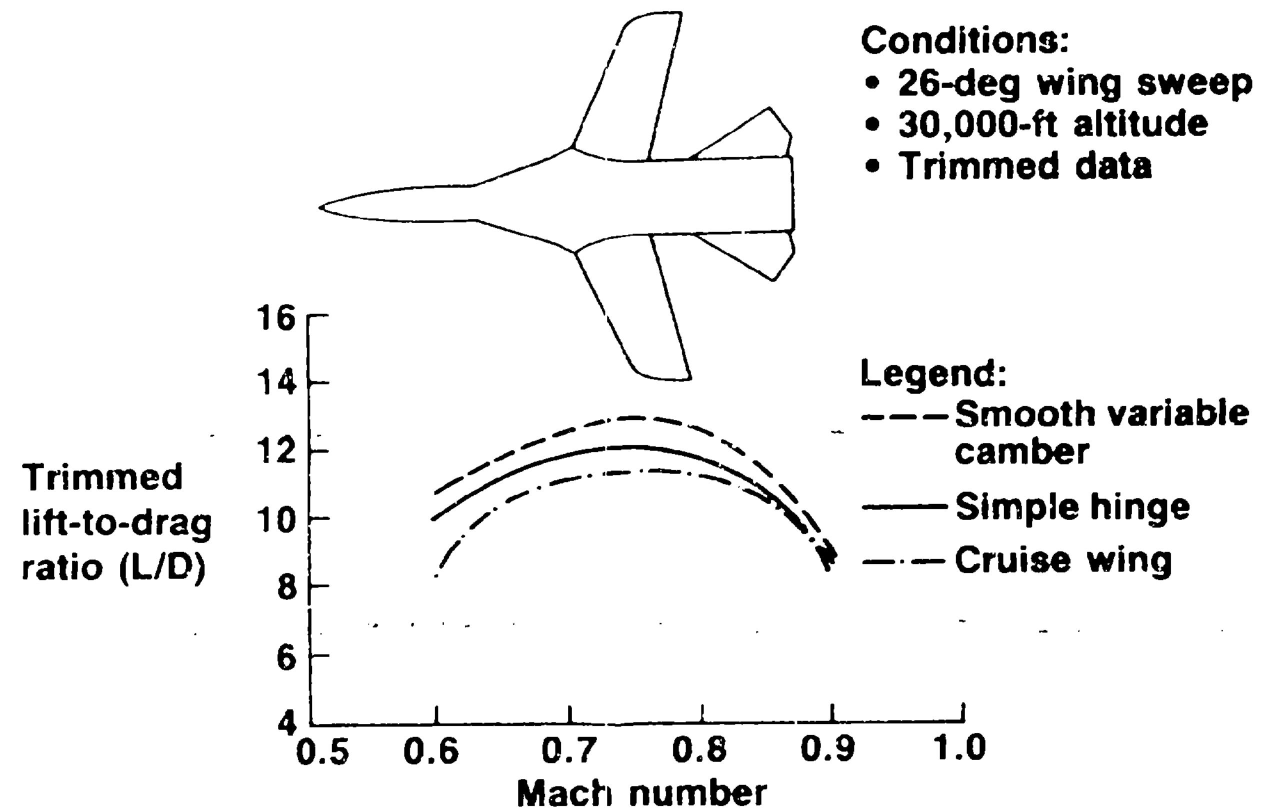
- Examine performance requirements
- Determine primary emphasis for variable camber system
- Select variable camber concept and extent
  - Simple hinge, smooth flexible skin, slotted
  - Leading edge and/or trailing edge
- Define operating requirements
  - Reflection magnitude and rate
  - Actuation power and concept
- Select materials and structural concept
- Evaluate design implications and performance
  - Drag
  - Weight
  - Mission Capability

# Design Considerations

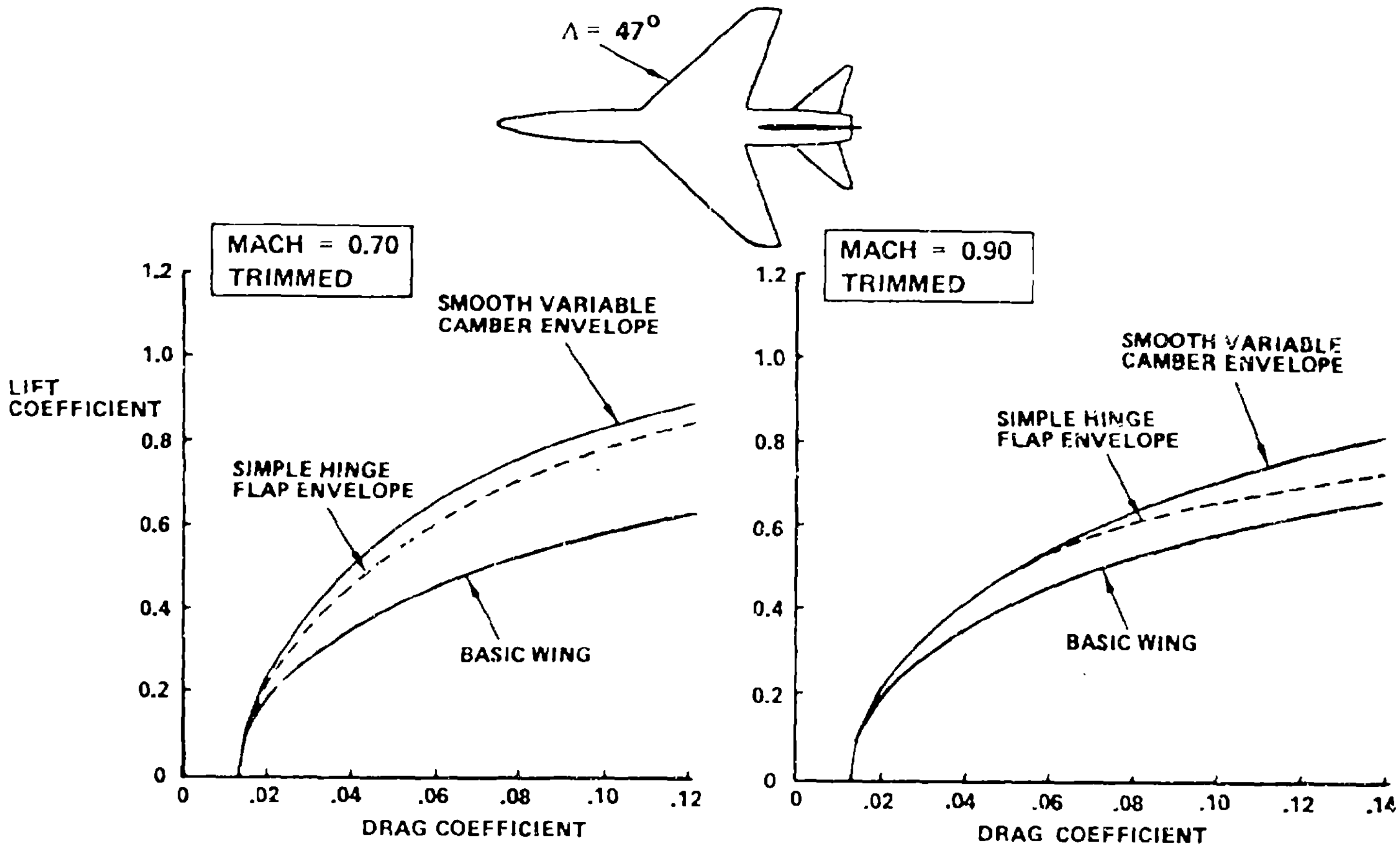
- Wing Geometry
  - Thickness Distribution
  - Chord of Moving Surface
  - Wing Close Out
  - End Seals
- Redundancy
- Duty Cycle
- Producibility
- Maintainability

DKG/4/19/002dm

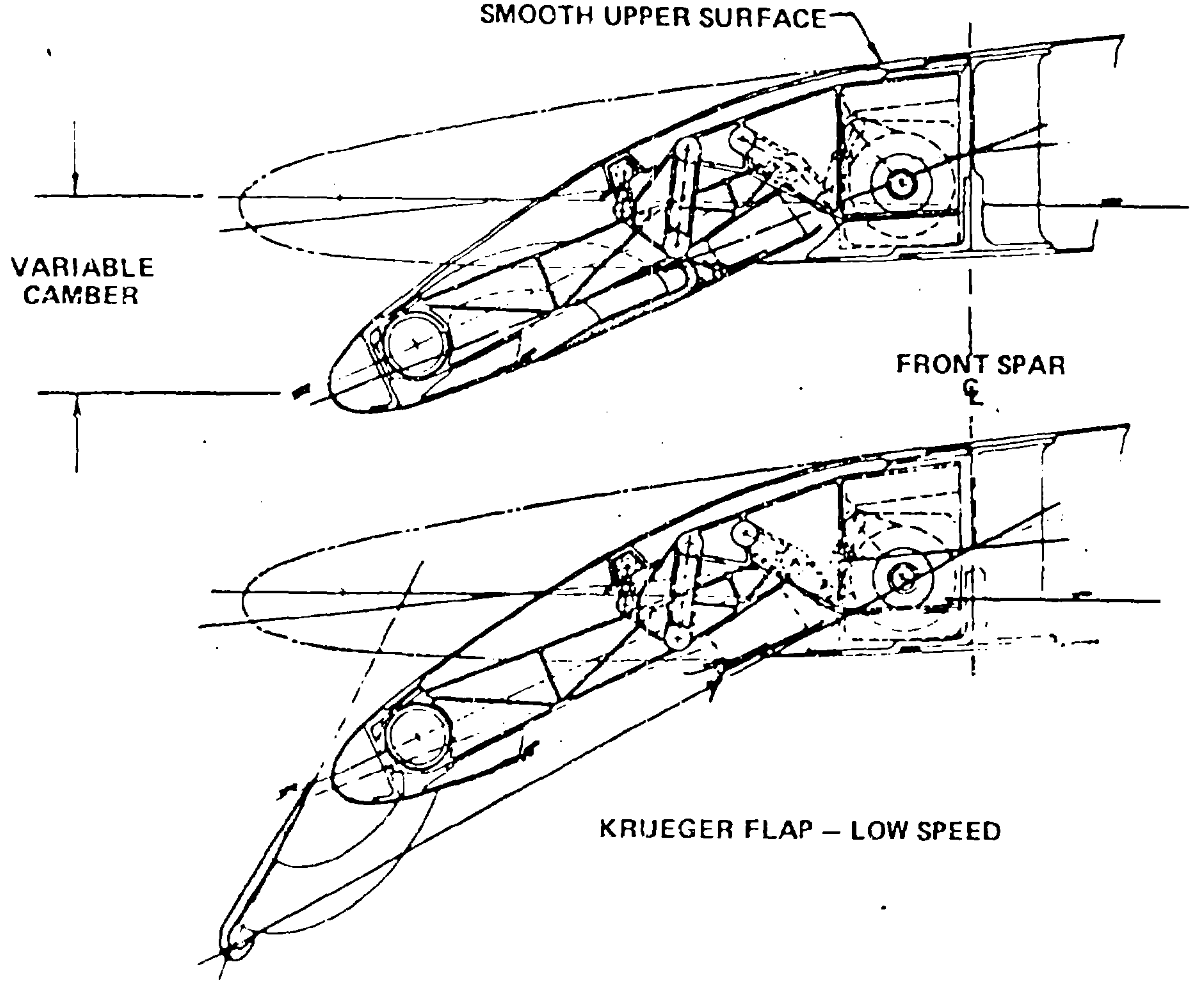
# Simple Hinge Versus Smooth Variable Camber



# Smooth Variable Camber vs. Simple Hinge Flap
# F-8



# Smooth Variable Camber Leading Edge with Auxiliary Krueger Flap



# Weight Considerations
# (Fighter-Type Aircraft)

| | Average Weight, lb/ft$^2$ |
|---|---|
| • Fixed-wing leading edge structure | 4.5 |
| • Simple-drooped leading edge flap | 10.0 |
| • Double-drooped leading edge flap | 12.0 |
| • Smooth variable-camber (AFTI production) | 16.0 |

# Conclusions

- The advantages of Mission Adaptive Wing capability have been recognized since the early days of aviation
- Advances in State-Of-Art technology in materials, Power Sources and Control Concepts now allow practical Mission Adaptive Wing systems to be built
- Aircraft having Performance Requirements in more than one flight regime can benefit greatly from Mission Adaptive Wing capability

SESSION VI

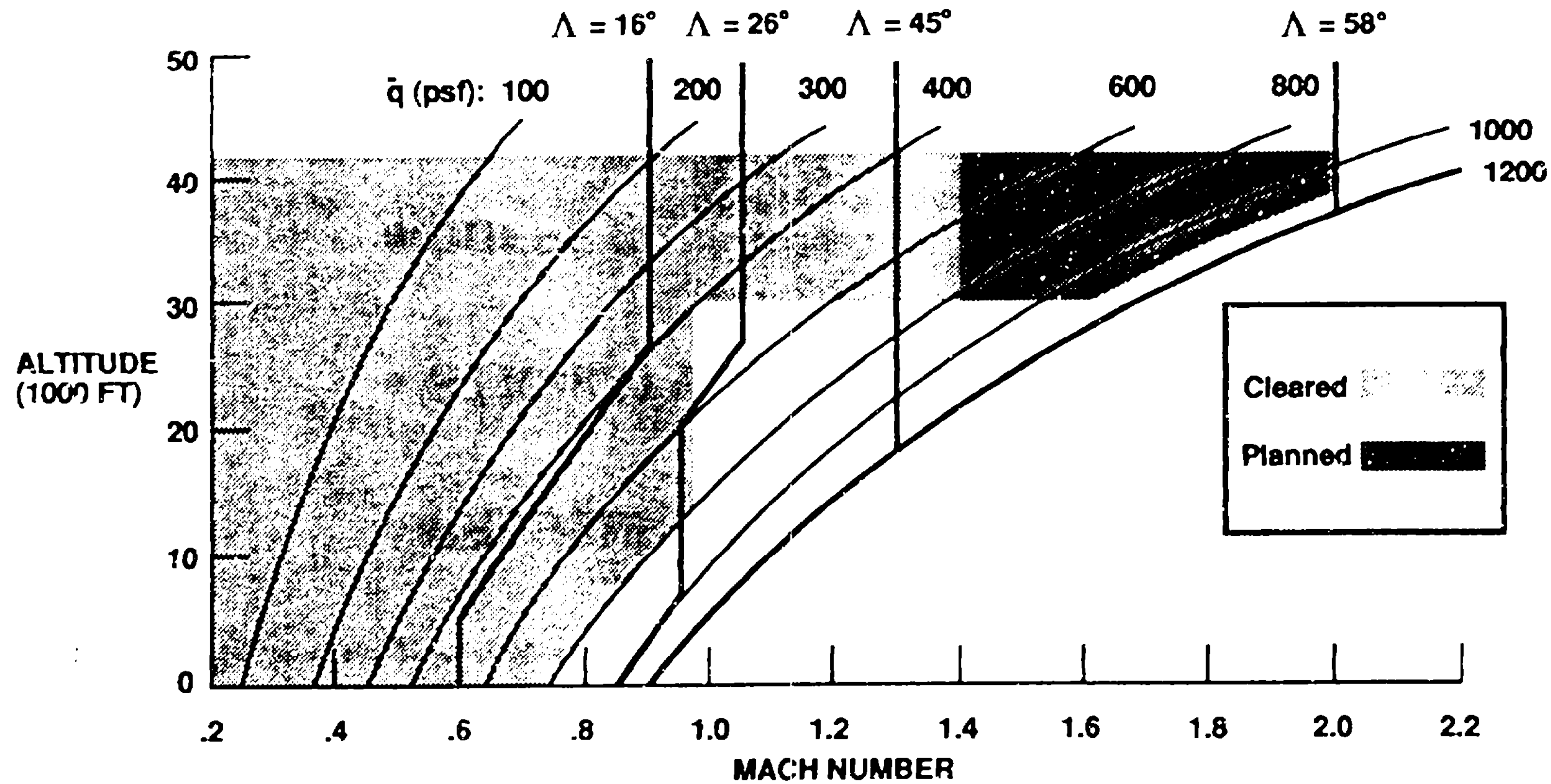
FUTURE RESEARCH


OVERVIEW
REMAINING FLIGHT TESTS
AFTI
39778
NASA

# REMAINING TASKS

- A/C MAINTENANCE
  - ENGINE (TCTO)
  - AIRFRAME (TCTO)
  - PYRO (TCTO)
- MAW SYSTEM
  - 125 HOUR INSPECTION
  - CCC MODE UPDATE
  - MEGA MODE EVALUATION
- FLIGHT TEST
  - JULY - AUG
  - OCT - DEC

# FLIGHT TEST ENVELOPE



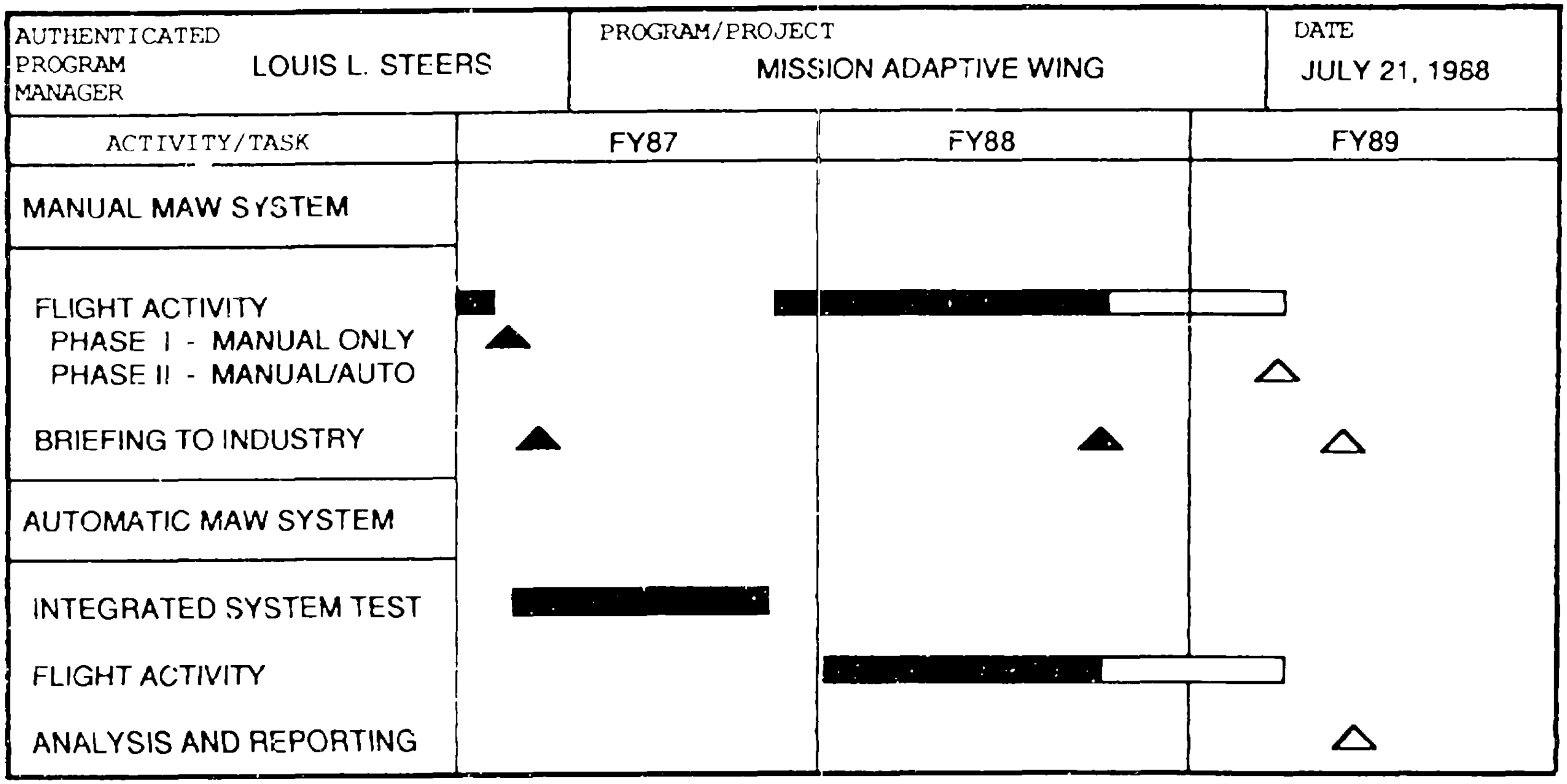
## MANUAL FLIGHT CONTROL SYSTEM - FLIGHT STATUS

- PRESSURE DISTRIBUTION
- STABILITY AND CONTROL
- BUFFET
- PERFORMANCE FLIGHT TEST
- AERODYNAMIC LOADS

# AUTOMATIC FLIGHT CONTROL SYSTEM - FLIGHT STATUS

- CRUISE CAMBER CONTROL (CCC)
- MANEUVER CAMBER CONTROL (MCC)
- MANEUVER LOAD CONTROL (MLC)
- MANEUVER ENHANCEMENT / GUST ALLEVIATION
- MODE COMBINATIONS

# SCHEDULE


AUTHENTICATED PROGRAM MANAGER
LOUIS L. STEERS
PROGRAM/PROJECT
MISSION ADAPTIVE WING
DATE
JULY 21, 1988
ACTIVITY/TASK
FY87
FY88
FY89
MANUAL MAW SYSTEM
FLIGHT ACTIVITY
PHASE I - MANUAL ONLY
PHASE II - MANUAL/AUTO
BRIEFING TO INDUSTRY
AUTOMATIC MAW SYSTEM
INTEGRATED SYSTEM TEST
FLIGHT ACTIVITY
ANALYSIS AND REPORTING